PAN-AFRICAN UNIVERSITY
INSTITUTE FOR WATER AND ENERGY SCIENCES
(including CLIMATE CHANGE)

Master Dissertation

Submitted in partial fulfillment of the requirements for the Master degree in

CLIMATE CHANGE

Presented by

Charteris Claude MAHOUNGOU

Socio-economics impacts of Coastal Erosion and Sea Level Rise under Climate Change in Pointe-noire Region (Republic of Congo)

Defend on 14/04/2025 Before the Following Committee :

Chair: Dr. Baahmed Djelloul	Professor at Sidi-Bel-Abbès University
Supervisor: Pr. Moukandi N'Kaya Guy	Professor at Marien Ngouambi University
External examiner: Dr. Adama FAYE	Institut de Recherches Agricoles, Senegal
Internal examiner: Pr. Kamila Baba Hamed	Professor at Tlemcen University

Academic year: 2024-2025

DECLARATION

I, CHARTERIS CLAUDE MAHOUNGOU, hereby declare that this thesis represents my personal work, realized to the best of my knowledge. I also declare that all information, material and results from other works presented here, have been fully cited and referenced in accordance with the academic rules and ethics.

Signature: Date: __25/03/2025____________________

CHARTERIS CLAUDE MAHOUNGOU

Certification

I undersigned, Prof. Dr. Guy MOUKANDI N'KAYA, Lecturer-Researcher at Marien NGouambi University, certify that CHARTERIS CLAUDE MAHOUNGOU conducting this master thesis under my supervision.

Signature: Date: 28/03/2025__________

Prof. Dr. Guy MOUKANDI N'KAYA

DEDICATION

In loving memory of my mother, whose love and wisdom continue to guide my steps.

To my sisters, the pillars of my life, for their strength and unwavering support.

And above all, to all those who suffer from the consequences of the environmental crisis. May this work contribute, however humbly, to raising awareness and inspiring action for a more just and sustainable future.

ACKNOWLEDGEMENT

First and foremost, I extend my deepest gratitude to the Lord God, the unchanging source of life and protection, for the health and strength He has granted me throughout this journey.

I am grateful to the African Union for their invaluable financial support, which made the realization of this research possible. I also thank the Algerian government for their warm welcome and for the opportunity to study in this country rich in culture and history.

My sincerest thanks go to Professor Zerga Abdellatif, Director of PAUWES, who has been an exceptional guide and mentor. I am deeply grateful for his constant support, benevolent guidance, infinite patience, and invaluable advice, which were crucial to my training.

I also thank the Rector of the University of Tlemcen, our host university, for welcoming us into its fold and for providing us with the resources necessary for our success.

I would like to express my gratitude to Dr. Moukandi N'Kaya for his guidance, insightful advice, and unwavering support in the completion of this work.

I warmly thank all the staff and coordinators of the Water, Energy, and Climate Change Department of PAUWES for their hard work and dedication throughout our training.

I am grateful to all my professors for sharing their valuable knowledge, which has enriched my journey and broadened my horizons.

I also thank Mr. Gervais Aurélien DIBANTSA, my internship supervisor, for his valuable advice and for welcoming me into his organization.

My warmest thanks go to my friends, particularly Adigbegnon Marcel, Paul Ndolo, Bimangou Glenn, and Bimangou Landry, for their constant support, friendship, and encouragement. I also thank my internship colleagues for their kindness and collaboration.

Finally, I would like to thank all those who, near or far, have contributed to the success of my journey within PAUWES. Your support has been a source of motivation and inspiration.

Abstract

This study examines the multifaceted challenges posed by climate change, coastal erosion, and sea-level rise in the Pointe-Noire region of the Republic of Congo. Analysis of historical data, future climate projections, and vulnerability assessments reveals a complex interplay between climatic factors, human activities, and coastal dynamics. The results indicate a trend of increasing climatic aggressiveness, exacerbating coastal erosion and threatening infrastructure, ecosystems, and local communities. Sea-level rise projections highlight the risk of coastal inundation, necessitating urgent and integrated adaptation strategies to protect the region and ensure a sustainable future. The study emphasizes the importance of climate monitoring, integrated coastal zone management, adaptation measures, sustainable economic development, community awareness, and regional and international cooperation.

Résumé

Cette étude examine les défis multiformes posés par le changement climatique, l'érosion côtière et l'élévation du niveau de la mer dans la région de Pointe-Noire, en République du Congo. L'analyse des données historiques, les projections climatiques futures et les évaluations de la vulnérabilité révèlent une interaction complexe entre les facteurs climatiques, les activités humaines et la dynamique côtière. Les résultats indiquent une tendance à l'augmentation de l'agressivité climatique, exacerbant l'érosion côtière et menaçant les infrastructures, les écosystèmes et les communautés locales. Les projections de l'élévation du niveau de la mer soulignent le risque d'inondation des zones côtières, nécessitant des stratégies d'adaptation urgentes et intégrées pour protéger la région et assurer un avenir durable. L'étude souligne l'importance de la surveillance climatique, de la gestion intégrée des zones côtières, des mesures d'adaptation, du développement économique durable, de la sensibilisation communautaire et de la coopération régionale et internationale.

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Abbreviations and Acronyms

- **ATL08:** Advanced Topographic Laser Altimeter System (part of the ICESat-2 mission)
- **CHIRPS:** Climate Hazards Group InfraRed Precipitation with Station data
- **CMIP5**: Coupled Model Intercomparison Project Phase 5
- **CNN:** Convolutional Neural Network
- **DEMs:** Digital Elevation Models
- **DRI:** Drought Risk Index
- **DSAS:** Digital Shoreline Analysis System
- **EPR:** Environmental Protection Regulations
- **GADM:** Database of Global Administrative Areas
- **GDP:** Gross Domestic Product
- **GPS:** Global Positioning System
- **IAC:** Interagency Agreement Clause
- **ICESat-2:** Ice, Cloud, and land Elevation Satellite 2
- **IPCC:** Intergovernmental Panel on Climate Change
- **LE90:** Linear Error at 90% confidence level
- **MIR:** Mid-Infrared
- **MNDWI:** Modified Normalized Difference Water Index
- **NASA:** National Aeronautics and Space Administration
- **NDWI:** Normalized Difference Water Index
- **NIDIS:** National Integrated Drought Information System
- **NIR:** Near-Infrared
- **NOAA:** National Oceanic and Atmospheric Administration
- **PAUWES:** Pan African University Institute for Water and Energy Sciences
- **PRCPTOT:** Annual Total Precipitation
- **R95p:** Very Wet Days (precipitation > 95th percentile)
- **R99p:** Extremely Wet Days (precipitation > 99th percentile)
- **RCP:** Representative Concentration Pathway
- **RMSE:** Root Mean Square Error
- **R95p:** Very Wet Days (precipitation > 95th percentile)
- **R99p:** Extremely Wet Days (precipitation > 99th percentile)
- **SLR:** Sea Level Rise
- **SWIR:** Shortwave Infrared
- **TN10p:** Cool Nights (minimum temperature < 10th percentile)

- **TN90p:** Warm Nights (minimum temperature > 90th percentile)
- **TNn:** Minimum of Minimum Temperature
- **TNx:** Maximum of Minimum Temperature
- **TX10p:** Cool Days (maximum temperature < 10th percentile)
- **TX90p:** Warm Days (maximum temperature > 90th percentile)
- **TXn:** Minimum of Maximum Temperature
- **TXx:** Maximum of Maximum Temperature
- **UMR:** Unité Mixte de Recherche (Joint Research Unit - a French research designation)
- **UN-Habitat:** United Nations Human Settlements Programme
- **UNDP:** United Nations Development Programme
- **UNESCO:** United Nations Educational, Scientific and Cultural Organization
- **WACA:** West Africa Coastal Areas Management Program
- WMO: World Meteorological Organization

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CHAPITER I: GENERAL INTRODUCTION

1. Context

Climate change and its impacts on coastal zones have become a major global concern (Nicholls & Cazenave, 2010). Sea-level rise, caused by the thermal expansion of the oceans and the melting of glaciers and ice caps, poses a major threat to coastal regions worldwide (IPCC, 2019). According to the Intergovernmental Panel on Climate Change (IPCC), mean sea level could rise by 0.26 to 0.98 meters by 2100, depending on greenhouse gas emission scenarios (IPCC, 2021). This rise in sea level, combined with coastal erosion, will have profound socio-economic consequences for densely populated coastal areas (Nicholls, 2021). A study by Kulp and Strauss (2019) estimates that by 2050, areas currently home to 300 million people will be threatened by annual coastal flooding, with economic losses that could reach 4.7% of global GDP in some regions (Kulp and Strauss, 2019).

The African continent is particularly vulnerable to the impacts of sea-level rise and coastal erosion due to its extensive coastlines, high population density in coastal areas and fragile infrastructure (Hinkel et al., 2012; Nicholls, RJ; Hanson, S.; Herweijer, C.; Patmore, N.; Hallegatte, S.; Corfee-Morlot, J.; Château, J.; UN-Habitat, 2009). According to the World Bank, around 25% of Africa's population lives in low-lying coastal areas (Barbier, 2015; World Bank, 2022; WACA and World Bank Group, 2018). These regions are home to major cities, vital international trade ports and valuable coastal ecosystems. A study by Dasgupta et al. (2009) found that a one-meter rise in sea level could affect more than 23 million people in West Africa's coastal cities alone, with economic losses estimated at $5.7 billion a year (Dasgupta et al., 2009, 2011). In addition, the African Union's African Climate Change Strategy (2022) highlights the need for adaptation measures to protect coastal communities and infrastructure from the impacts of sea-level rise and coastal erosion (African Union, 2023).

The Republic of Congo, a Central African country, is not immune to these challenges. The city of Pointe-Noire, the country's main seaport and second-largest city, is particularly vulnerable. Situated on a narrow strip of coastline, Pointe-Noire is home to some 1.5 million inhabitants and hosts a significant proportion of the country's economic activities, notably oil, timber and port operations (Logistics Cluste, 2022; Maloueki, 2009; Tati, 2008; Trésor, 2024). Coastal erosion, exacerbated by rising sea levels, threatens the city's coastal infrastructure, housing and economic activities. A study by the Observatoire national des changements environnementaux revealed that some areas of Pointe-Noire lost up to 200 meters of coastline between 1986 and 2016 (Mboumbou et al., 2022; MEDDBC, 2021; Sitou et al., 2024; UNDP, 2011).

Given the socio-economic importance of Pointe-Noire to the Republic of Congo and its vulnerability to the impacts of climate change, it is crucial to study the potential effects of coastal erosion and sea-level rise on this region. A better understanding of these issues will enable the development of appropriate adaptation and mitigation strategies to protect the region's coastal communities, infrastructure and key economic activities.

2. Problem statement

Pointe-Noire and its surrounding area, including the Loango region, occupy an important position in the Republic of Congo. Geographically, Pointe-Noire lies on a narrow coastal strip along the Atlantic Ocean, bordered by the Kouilou River to the north and the Loango National Park to the south (Maloueki, 2009). Economically, Pointe-Noire is the country's economic hub, home to the country's main seaport, which handles the majority of Congo's maritime trade, including exports of oil, timber and other natural resources (Maloueki, 2009). Demographically, Pointe-Noire is the second largest city in the Republic of Congo, with a population of around 1.5 million, almost a quarter of the country's total population (Tresor, 2024).

However, this strategically important coastal region faces a serious threat from coastal erosion, which is rapidly eroding the shoreline and endangering infrastructure, housing and economic activities (Mboumbou et al., 2022). Alarming rates of coastal erosion, with some areas of Pointe-Noire losing up to 200 metres of coastline between 1986 and 2016 (Mboumbou et al., 2022). This erosion has already led to significant economic losses, with the destruction of coastal roads, buildings and valuable seaside property (Mounganga, 2009). In addition, Loango National Park, a renowned ecotourism destination and UNESCO World Heritage Site, is also facing encroaching coastal erosion, threatening its unique ecosystem and biodiversity (Ekhalie et al., 2019).

Added to this problem is the imminent threat of sea-level rise caused by global climate change. Scientific projections indicate that global average sea level could rise by between 0.26 and 0.98 meters by 2100, depending on greenhouse gas emission scenarios (IPCC, 2021). This rise in sea level will exacerbate coastal erosion, potentially submerging low-lying areas in and around Pointe-Noire, and increasing the frequency and severity of coastal flooding (Nicholls, 2021).

The socio-economic consequences of coastal erosion and sea-level rise in the Pointe-Noire region could be severe. Economic sectors such as maritime trade, the oil and gas industries and tourism, which are vital to the Congolese economy, are likely to be disrupted and suffer substantial financial losses (Maloueki, 2009). In addition, the displacement of coastal communities and the destruction of housing and infrastructure could lead to major social upheaval, exacerbating problems such as poverty, public health issues and internal migration (IPCC et al., 2019; Kamdoum J., Adewumi, 2020).

Given the strategic importance of Pointe-Noire and the surrounding area, it is imperative to undertake an in-depth study to assess the potential impacts of coastal erosion and sea-level rise on this region. This research aims to provide a detailed analysis of risks and vulnerabilities, and to explore adaptation and mitigation strategies to protect the region's economic activities, infrastructure and communities from the imminent consequences of climate change.

3. Research questions

3.1. General research question

What will be the socio-economic impacts of climate change-related coastal erosion and sea-level rise in the Pointe-Noire region in the Republic of Congo?

3.2. Specific research questions

- ☑ How have past climate variabilities influenced coastal erosion rates and patterns in the study area, and what are projected future changes in relevant climate parameters?
- ☑ What are the historical rates and patterns of coastal erosion in the Pointe-Noire and Loango regions, and how are they expected to evolve under future climate scenarios.
- ☑ What are the potential socio-economic impacts of coastal erosion and sea-level rise on the study area, taking into account factors such as infrastructure damage, economic disruption and community displacement?

4. Research hypotheses

4.1. General hypothesis

Coastal erosion, sea-level rise and other socio-economic facts show the consequences of changes in the Pointe-Noire and Loango regions of the Republic of Congo.

4.2. Specific hypothesis

- ☑ Extreme climatic events are at the root of coastal erosion, sea-level rise and other social and economic trends in the study region.
- ☑ The Pointe-Noire and Loango regions have experienced significant coastal erosion in recent decades, and this erosion is expected to accelerate under future climate

scenarios, posing significant threats to infrastructure, economic activities and coastal communities.

- ☑ The socio-economic impacts of coastal erosion and sea-level rise in the study area will be significant, resulting in damage to infrastructure, disruption to economic sectors such as maritime trade and tourism, and displacement of coastal communities.

5. Research objectives

5.1. General objective

The general objective of this study is to assess the impact of climate change in the Pointe Noire and Loango regions of the Republic of Congo.

5.2. Specific objectives

The specific objectives are to:

- ☑ Analyze climate change and its consequences in the Pointe Noire region and the Loango region of the Republic of Congo.
- ☑ Study the dynamics of coastal erosion and its implications on the degradation of infrastructure and economic activities and coastal communities in the Pointe Noire region and the Loango region of the Republic of Congo.
- ☑ Assess the socio-economic impacts of coastal erosion and sea-level rise in the study area, as well as damage and disruption to economic sectors in the Pointe Noire region and the Loango region of the Republic of Congo.

6. Relevance of the study

This study is of major social, economic, environmental and scientific importance. Firstly, it provides a better understanding of the mechanisms associated with climate change and their impact on the coast. These phenomena, such as sea-level rise and more frequent storms, are crucial for predicting future environmental changes. Secondly, it shows that coastal regions are home to a large proportion of the population of Pointe Noire and the Loango region in the Republic of Congo. Erosion and marine advance have had devastating consequences on the infrastructure, habitat and livelihoods of local populations in these regions of the Congo. In scientific terms, it has helped to develop adaptation strategies to reduce the negative impacts of extreme climatic phenomena. The results of this study could inform and influence political decisions in the implementation of laws and regulations to protect coastal zones in Congo. Finally, the present research enriches scientific research by providing new data specific to the Pointe Noire and Loango regions of the Republic of Congo. It serves as a reference for future work, particularly in the field of environmental sustainability.

7. Scope of the study

The scope of the present study on climate change, coastal erosion and marine encroachment is vast, multidimensional and covers several key aspects. Geographically, the study can focus on a specific region, such as a particular coastline, or take a broader approach, examining several coastal zones affected by the same phenomena. This can include comparisons between different regions of the world, enabling global and regional trends to be identified. In terms of temporal perspectives, it allows us to examine the past, present and future effects of climate change on coasts. This involves retrospective analyses to understand the historical evolution of coastal erosion, and predictive models to anticipate future changes. The study also examines the ecological consequences of erosion and marine encroachment, assessing impacts on biodiversity, natural habitats and ecosystem services. This includes the study of impacts on wetlands, coral reefs and other sensitive coastal ecosystems.

Beyond the physical and ecological aspects, the study explored the socio-economic consequences for coastal communities. . This includes the impact on infrastructure, the local economy, forced migration, and cultural losses, as well as the economic costs of adaptation measures. A significant part of the scope included the identification and assessment of existing or potential adaptation strategies, such as nature-based solutions (e.g. mangrove restoration) or protective infrastructure (e.g. dykes and breakwaters). The study also served to propose recommendations for coastal risk management at different levels, from local to international. Finally, this study could pave the way for further research. It lays the foundations for doctoral projects, applied field research and interdisciplinary collaborations involving climatologists, geologists, economists and sociologists. The scope of the present study is broad, with important implications for science, coastal risk management, public policy, and the protection of coastal populations and ecosystems.

8. Background of the study

8.1. Biophysical and human characteristics of the study region

The Pointe-Noire and Loango region, located on the south-western coast of the Republic of Congo, has a varied and strategically important geographical area, combining urban, industrial, coastal and natural zones.

8.1.1. Climatic conditions in the study area

The Pointe-Noire and Loango region, located on the Atlantic coast of the Republic of Congo, has a tropical climate, influenced by the Atlantic Ocean and proximity to the equator. Due to intense rainfall during the rainy season, the region can be prone to flooding, particularly in low-lying areas. In addition, coastal erosion is a recurring problem, exacerbated by rising sea levels and marine storms. These climatic conditions make the Pointe-Noire and Loango region both rich in biodiversity and vulnerable to climatic hazards, making it a particularly relevant subject for research into climate change and coastal erosion. The region is characterized by a tropical climate with a marked rainy and dry season. Describing the various climatic elements of the study region provides a better understanding of its meteorological characteristics.

8.1.2. Temperatures

The region enjoys relatively stable temperatures throughout the year, with annual averages varying between 24°C and 28°C. Seasonal variations are low, typical of tropical climates. In a context of global climate warming, this area, located off the ocean coast, is subject to a number of serious consequences due to marine encroachment and coastal erosion (MASSOUANGUI-KIFOUALA et al. 2023).

8.1.3. Precipitation

The Pointe-Noire and Loango region has a marked rainy season, generally extending from November to April. During this period, rainfall can be abundant, with accumulations exceeding 1,500 mm per year (MASSOUANGUI-KIFOUALA and al. 2023). The dry season, on the other hand, extends from May to October, with much lower rainfall, or even virtually non-existent during certain months. A phenomenon is said to be dynamic when it does not stagnate, but changes over time. According to E. Amoussou (2010) explains that environmental dynamics are also manifested by erosion driven by runoff water, which removes sandy, clayey materials and plant debris, transporting them and depositing them at the bottom, thus determining the succession of facies at the bottom of rivers and lakes.

8.1.4. Humidity

Relative humidity is high throughout the year, due to the proximity of the ocean. During the rainy season, humidity can exceed 90%, contributing to a more intense sensation of heat (MASSOUANGUI-KIFOUALA and al. 2023).

8.1.5. Oceanic influence

The Atlantic Ocean moderates temperatures, but it is also the source of sea winds that can sometimes be quite strong, especially during the dry season. These winds can also bring coastal fogs, especially between June and September.

8.1.6. Sea currents and upwelling

The region is influenced by the cold Benguela current, which causes upwelling along the coast. This phenomenon can affect water temperature and have repercussions on local marine ecosystems.

8.1.7. Relief and landscape

This section describes the coastline, beaches, relief, wetlands and lagoons. The region's coastline is made up of fine sandy beaches, often bordered by dunes and mangroves. The beaches of Loango are particularly renowned for their wild beauty and biodiversity. The region is predominantly flat, with some modest relief in the form of hills. Altitude varies slightly, not exceeding 150 meters above sea level. The region includes several wetlands and lagoons, which are ecosystems rich in biodiversity. These areas are essential for migratory birds.

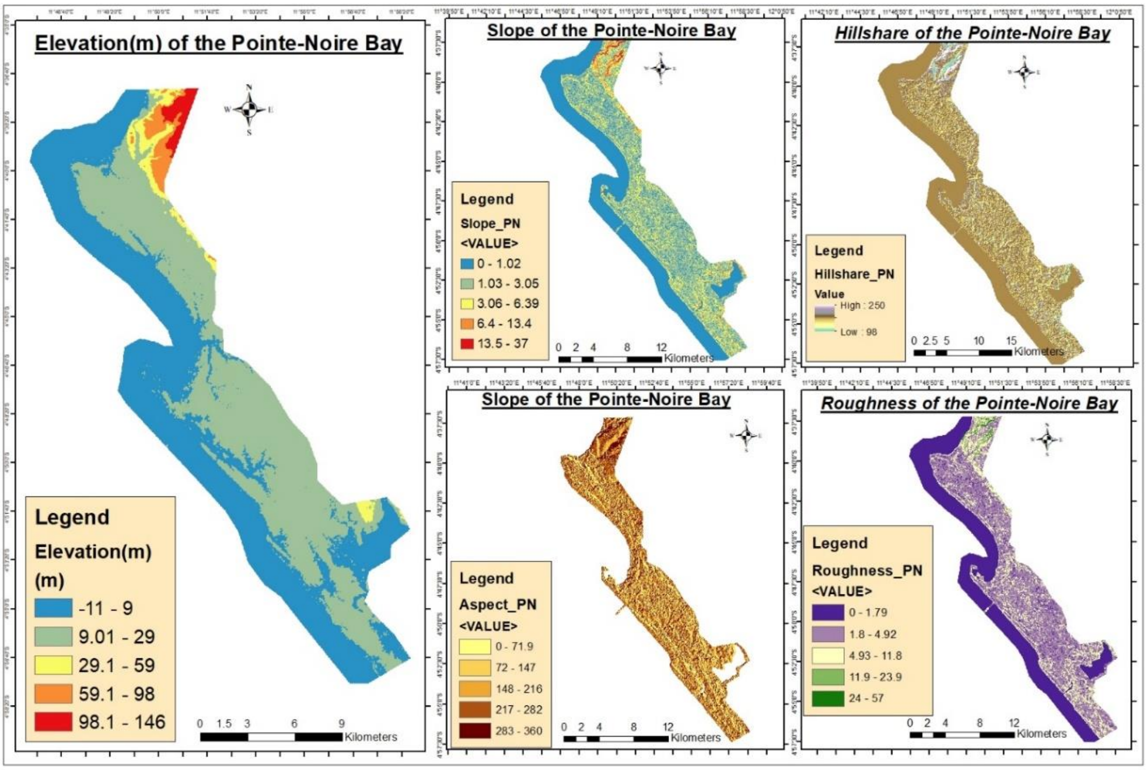

Figure 1: Orographic characteristics of the study area.

Analysis of Fig.1 shows that the study area has a high relief to the north, with altitudes ranging from 283 to 360 mm, and a very high roughness of 24 to 57. In addition, the extreme north of the study area is dominated by very high hill ranges reaching 200 metres in altitude, with relatively steep slopes of 6.4 metres 37 metres in the extreme north-west and very gentle slopes in the extreme north-east. The rest of the region is relatively heterogeneous, with the exception of the south-west, which appears to be homogeneous.

8.2.Hydrography

The region is crossed by several small rivers and streams that flow into the Atlantic Ocean. These rivers and streams play an important role in draining and feeding wetlands. This is one of the region's main lagoons, located in the Conkouati-Douli National Park. It is home to a rich biodiversity, including hippos, crocodiles and numerous bird species.

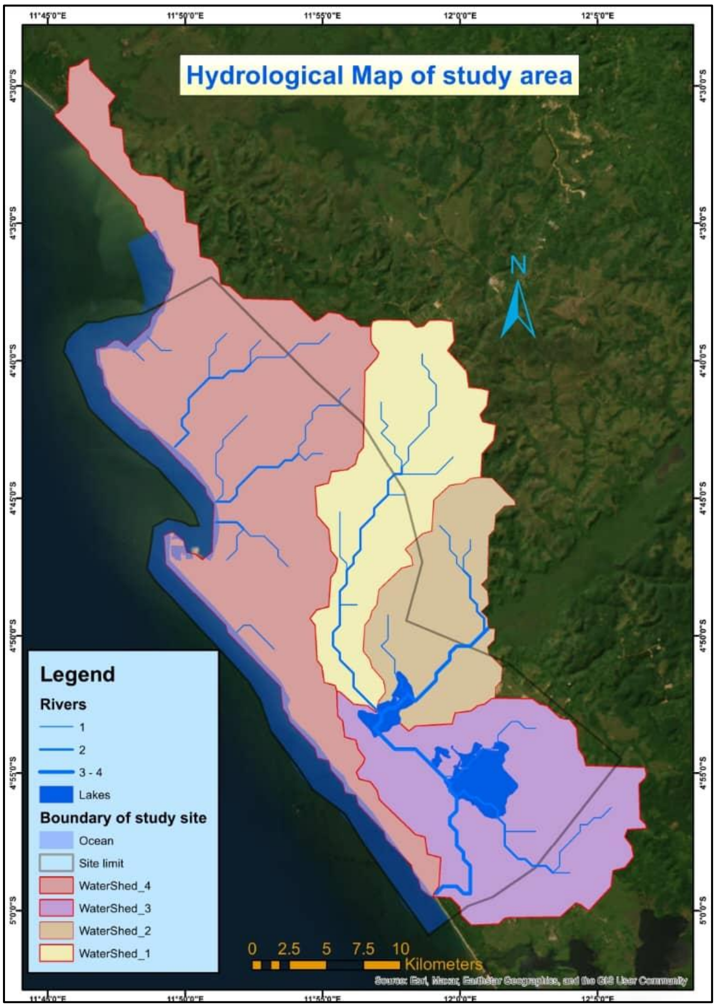

Figure 2: Hydrographic network of the study area.

The northern part of the study area is also covered by a number of important waterholes and rivers, which are present in all localities. The hydrographic network in the southern part of the area is crossed by level 3 and 4 watercourses and is made up of numerous lakes. In addition to these rivers, there are numerous waterholes and streams fed by the waters of these rivers and by rainwater. This uneven distribution of rivers, streams and waterholes, and the proximity of the study area to the ocean, is nonetheless conducive to the development of socio-economic activities such as agriculture, livestock breeding and artisanal fishing, as well as being essential capital for plant formations and the water cycle through evaporative processes. Their overflow during the rainy season obstructs passage for users of the tracks and roads crossing these waters, but also poses a serious threat to the health and mobility of towns located near their banks.

8.3. Soil characteristics

Pointe Noire and Loango, located on Congo's Atlantic coast, have interesting soil characteristics that influence their environment and use (figure).

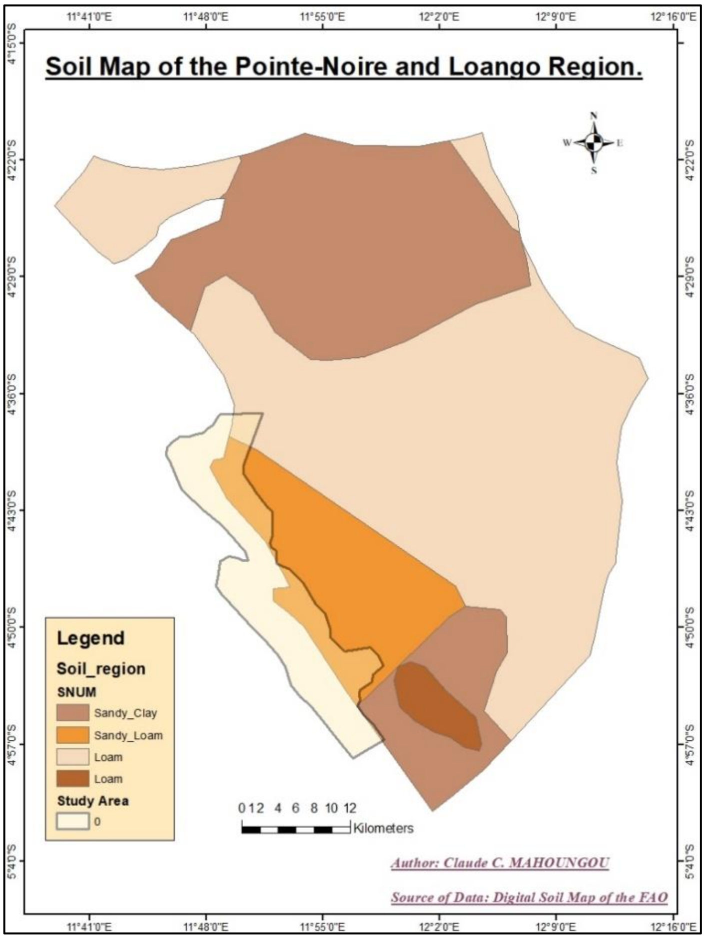

Figure 3: Soil characteristics of the study area.

Analysis of Fig.3 reveals two main soil types at Pointe Noire and Loanga: ferrallitic and alluvial. Ferrallitic soils are typical of tropical regions, often rich in iron oxides and reddish in color. They are well drained but can be poor in nutrients. As for alluvial soils, they drain along rivers and in flood-prone areas, we find alluvial soils richer in organic matter and nutrients, favorable to agriculture. These soils are highly variable in texture, mainly sandy to clayey, influencing their water retention and drainage capacity. The structure of these soils is often granular or aggregated, which affects porosity and aeration. In the study area, soils can be acidic, limiting the availability of certain nutrients to plants, but with very limited fertility requiring fertilization practices for agriculture. In addition, erosion is a concern in these areas, particularly due to deforestation and unsustainable agricultural practices. This can lead to topsoil loss and soil degradation.

8.4. Natural ecosystems : Mangroves forest

Mangroves, particularly present around wetlands and estuaries, play a crucial ecological role, protecting coastlines from erosion and acting as nurseries for numerous marine species.

Figure 4: Mangrove forest in Pointe-Noire.

Satellite imagery of Pointe-Noire highlights a mangrove forest of around 9 hectares along the coast, at the likely mouth of the Songolo River, underlining its crucial role in coastal protection against erosion and storms thanks to its stabilizing roots, as well as its importance for biodiversity by sheltering various species and acting as a carbon sink. However, its proximity to urbanized areas, illustrated by the road network and the presence of the “Mazra Club”, suggests potential pressures such as pollution, deforestation and urbanization, threatening its survival and underlining the need for sustainable management to preserve its ecological functions and the services it provides to the local population.

8.5. Urban development

As the economic heart of the Republic of the Congo, Pointe-Noire, a city on the Atlantic coast of west-central Africa, is undergoing rapid urbanization and development, stimulated by the oil industry and its deep-water port. This expansion, on a territory of 114,400 ha made up of plateaus separated by unhealthy areas, is putting considerable pressure on the environment, particularly on coastal ecosystems. With a population of over 1,400,000 spread over four communes, 48% of whom are under the age of twenty and 33% unemployed, the challenges of sanitation and communications, exacerbated by the topography, combine with the impact of urbanization on the environment. The sustainable management of this development is therefore crucial to reconciling economic, social and environmental imperatives, while taking into account the city's specific demographic and linguistic characteristics (UN Habitat, 2012).

CHAPTER II: LITERATURE REVIEW

This literature review chapter explores current knowledge on the socio-economic impacts of coastal erosion and sea-level rise under climate change in Pointe-Noire, Cong. It examines the key contributions of researchers and experts in the field, highlighting theoretical approaches, methodologies employed and main results obtained. The aim is to provide a comprehensive and critical overview of existing work, identify gaps and controversies, and situate the present study within the wider context of research on coastal erosion and sea-level rise. This analysis will make it possible to justify the relevance and originality of the research carried out, and to define future lines of development.

1. Climate variability in the Loango region

Studies of climate variability in the Loango region have provided insight into past and future climate patterns. For example, Smith et al. (2015) analyzed historical climate data in the Republic of Congo, including the Loango region, to identify fluctuations in temperature and precipitation. Their study highlighted the presence of both short- and long-term climatic variations in the region. Ondoua et al (2017) studied the impacts of climate variability on agricultural production in the Republic of Congo. Their research highlighted the importance of understanding climate patterns for sustainable agricultural practices in the Loango region. Amienyo et al (2020) conducted a study on climate variability and its effects on water resources in the Congo Basin. Their research highlighted the need for integrated water resource management strategies to address climate-related challenges in the Loango region.

2. Past and future coastal erosion and its socio-economic impacts

To assess past coastal erosion and its socio-economic impacts, several studies have focused on similar coastal regions. Johnson et al (2012) conducted an analysis of coastal change using satellite imagery and historical records to assess coastal erosion in the Gulf of Guinea. Their study revealed significant erosion rates along the coast of the Pointe-Noire region, highlighting the vulnerability of coastal infrastructure and communities. Duvat (2019) examined long-term trends in coastal erosion in West Africa, including the Gulf of Guinea. By analyzing historical shoreline changes, the study provided insight into the magnitude and spatial patterns of erosion, highlighting the need for effective coastal management strategies. Temmerman et al (2013) conducted a study on the socio-economic impacts of coastal erosion in West Africa. Their research highlighted the economic consequences of erosion, particularly in densely populated coastal areas, highlighting potential socio-economic implications in the Pointe-Noire region.

Coastal erosion is a major phenomenon affecting the coastal zones of Central Africa. The countries of this region, including Congo, are particularly vulnerable due to their low-lying coastal geography and the predicted rise in sea level linked to climate change. Several studies have already addressed this issue, providing important information. UNESCO's technical report on coastal vulnerability in Central Africa (2020) provides a comprehensive overview of impacts such as flooding, erosion, saline intrusion, loss of wetlands and emergent lands. It highlights the need for a coordinated regional approach to build resilience.

National studies such as that by Mounganga (PowerPoint link) in Congo have also analyzed erosion dynamics and their socio-economic consequences at local level in greater detail. But it does not assess future impacts under the effect of climate change. The study by Sara (2021) specifically assessed erosion in Pointe-Noire Bay, Congo. However, its approach remains descriptive, with no detailed figures on erosion rates and speeds. Sitou (2023) explores the links between coastal erosion and climate change from a long-term geomorphological perspective. But it lacks an in-depth analysis of the various components of sea-level rise.

However, despite these advances, a number of gaps remain:

- ☑ a still partial understanding of erosion processes at different spatial and temporal scales
- ☑ A lack of reliable quantitative data on erosion rates at several sites.
- ☑ Limited projections of future impacts of climate change
- ☑ Lack of concrete, locally-tested adaptation and mitigation solutions.
- ☑ Little consideration of the human and socio-economic dimensions of erosion.

This study will provide up-to-date field data, adopting a multidisciplinary approach focused on the affected populations. It will help fill some of these important gaps for better management of this major coastal hazard in Congo in particular, and Central Africa in general.

3. Risks of sea-level rise and potential socio-economic impacts

On a global scale, the 6th IPCC assessment report (2021) confirms an accelerated rise in sea levels due to global warming. By 2100, projections range from 0.28 to 1.01 meters of rise, depending on the different greenhouse gas emission scenarios. This rise is mainly due to the thermal expansion of the oceans and the melting of ice caps and glaciers. In this densely populated region, characterized by a wide strip of low-lying coastline, rising sea levels represent a serious threat. The UNESCO (2020) report on coastal vulnerability stresses that coastal erosion and coastal flooding already observed are likely to worsen considerably. However, this regional report remains rather qualitative and generalist on this issue. It lacks precise quantitative projections of the physical and socio-economic impacts of sea-level rise on a national and local scale.

To understand the risks of sea-level rise and its socio-economic impacts, several studies have examined similar coastal zones. Nicholls et al (2014) conducted a comprehensive assessment of the impacts of sea-level rise on coastal zones worldwide. Their research has led to a better understanding of the potential socio-economic consequences, including population displacement and loss of infrastructure and economic activities. Akinbode et al (2018) investigated the vulnerability of coastal communities to sea-level rise in West Africa. Their study highlighted the social and economic implications of sea-level rise, underscoring the need for adaptation measures in vulnerable areas such as the Pointe-Noire region. Adger et al (2016) examined the social and economic implications of sea-level rise in coastal regions around the world. Their research highlighted the importance of considering social factors and adaptive capacities when assessing the potential impacts of sea-level rise on communities and economies.

4. CoastalDEM as a foundation for coastal flood vulnerability assessment

In this literature review, we examine the crucial role of digital elevation models (DEMs) in assessing vulnerability to coastal flooding. Climate Central's CoastalDEM v3.0 stands out as a leading DEM, designed specifically for flood risk analysis on a global scale, from the poles to the equator. Drawing on years of scientific research and high-quality elevation data, CoastalDEM v3.0 enables accurate elevation modeling in coastal areas, providing a solid basis for flood risk prediction for local and global communities. Key technological enhancements in this version include a fusion of global elevation models, integration of updated input variables, extended coverage to the poles, elevation corrections up to 120 meters, and training based on NASA ICESat-2 data (S. A. Kulp and B. H. Strauss, 2020 ; Climate Central, 2022).

The performance and validation of CoastalDEM v3.0 demonstrate its superiority over other available DEMs. It boasts improved vertical accuracy, lower vertical error and reduced bias. Measurements of root mean square error (RMSE) and 90th percentile linear error (LE90) are the lowest among global DEMs, particularly in low-lying areas. The consistency of its performance at different spatial scales and independent validations confirm its reliability. In conclusion, CoastalDEM v3.0 provides a solid and accurate foundation for assessing vulnerability to coastal flooding, thanks to its technological improvements and validated performance (S. A. Kulp and B. H. Strauss, 2020 ; Climate Central, 2022).

CHAPITER III: METHODOLOGY FOR REASERCH

This chapter details the methodological approach adopted to answer the research questions and achieve the objectives defined in this study. It describes the strategic choices made regarding research design, data collection, and data analysis, justifying their relevance and suitability to the specific context of the study. The aim of this chapter is to provide complete transparency regarding the procedures followed, thereby enabling a rigorous evaluation of the validity and reliability of the results presented in subsequent chapters. It addresses the following aspects: the nature of the research (qualitative, quantitative, or mixed methods), the population and sample studied, the data collection instruments used, the data collection procedures implemented, and the data analysis methods employed.

1. Site Location and Description

Pointe-Noire Bay is located on the Congolese coast in the Republic of Congo. It is bordered to the south by Cape Pointe-Noire and to the north by the rocky spurs of Pointe Indienne, forming an elongated "S" curve over a distance of 18 km between 4°74'74" South latitude and 11°82'63" East longitude (Sitou et al., 2024). The coastal region of Congo is composed of three main geomorphological units: To the west, the Mayombe mountain range, about fifty kilometers from the coast, followed by vast tabular plateaus cut to the east by deeply incised valleys, and ending with a composite coastal fringe to the west, {a slightly undulating coastal plain at low altitude (less than 10 meters), separated from the plateaus by a steep slope of about 100 meters in height. The coastline is marked by two major bays: Pointe-Noire and Loango (Mboumbou et al., 2022). Pointe-Noire, located approximately 510 km southwest of Brazzaville, the capital of Congo, is the second largest city in the country and its main seaport. It is situated on a narrow coastal strip bordered by the Atlantic Ocean to the west. As for Loango, located north of Pointe-Noire, Loango is a small town known for its national park, the Conkouati-Douli National Park, and its natural beaches. Loango is about 30 km north of Pointe-Noire. Figure () presents the geographical location of the study area.

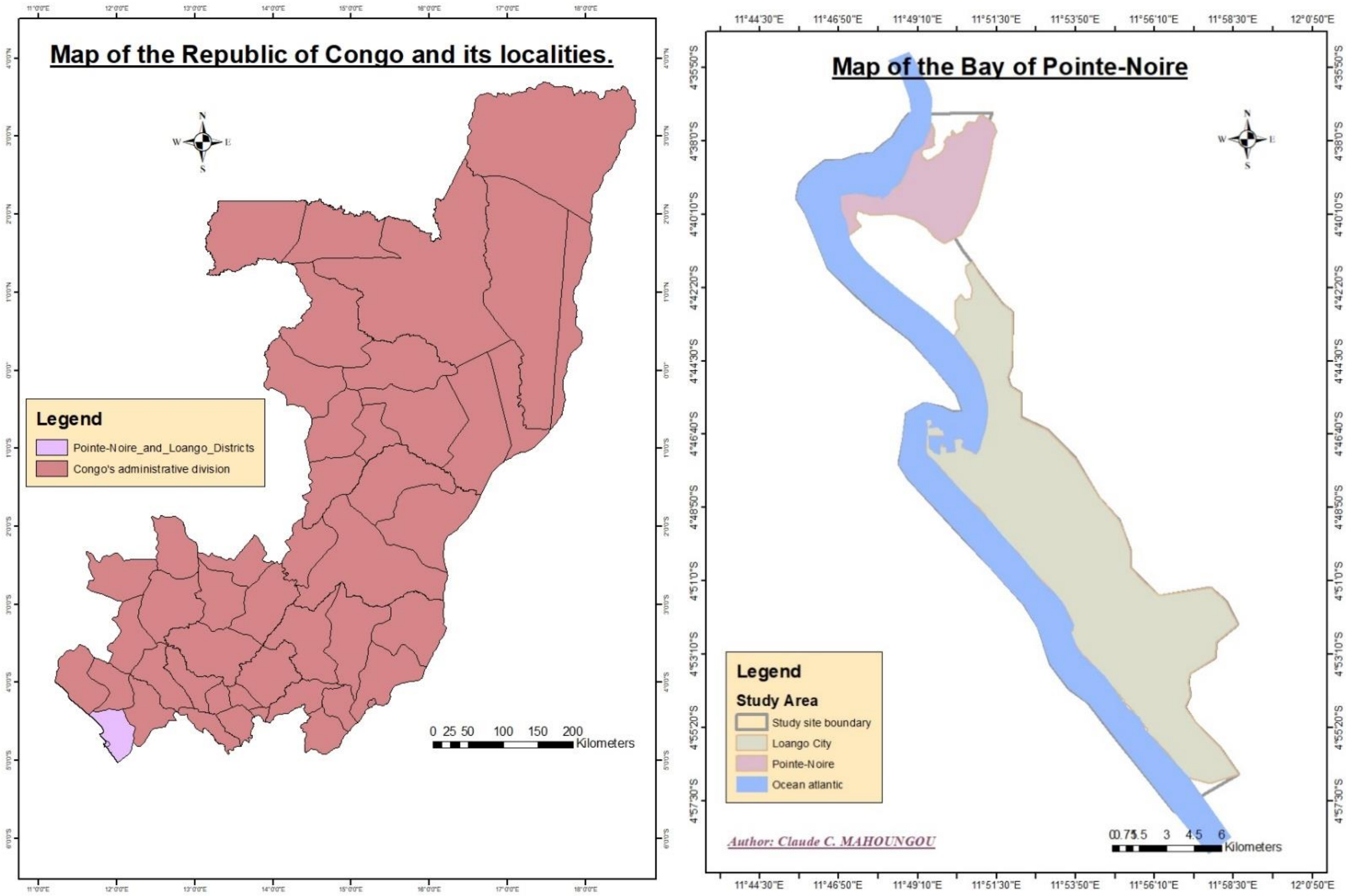

Figure 5: Geographical location of the study area.

2. Data Collection and Analysis Process

The study of climate change and coastal erosion in Pointe-Noire requires a rigorous methodology combining remote sensing, climate modeling, and analyses.

2.1. Spatial and Cartographic Data

2.1.1. Coastal Erosion Data

Past and present shoreline data are necessary to assess coastal erosion. Sentinel satellite imagery from Coopernicus Open Data (https://scihub.copernicus.eu), high-resolution imagery from Digital Earth Africa (https://www.digitalearthafrica.org), topographic records to be obtained in the field, LandSat 8 images for land use and land cover (https://www.usgs.gov/landsat-missions/landsat-8), and previous studies can provide valuable data. In addition, coastal digital elevation models (DEMs) with a resolution of 30 m will be downloaded from the USGS ASTER and SRTM databases.

2.1.2. Sea Level Rise Data

For the analysis of sea level rise, this study utilized CoastalDEM v3.0, a global digital elevation model (DEM) specifically designed for coastal flood risk assessment. CoastalDEM v3.0 inherently integrates:

- ✓ Base Elevation Models ; a fusion of multiple global DEMs (specific models not explicitly named in this section but implied to be recent and advanced).
- ✓ ICESat-2 v6 Data: NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission, version 6 (ATL08 dataset), providing global lidar-derived elevation measurements.
- ✓ 2019 World Settlement Footprint Dataset ; used for identifying buildings in densely populated areas to implement the building removal process.
- ✓ Population Density Data, used as an input variable and for triggering the building removal process in densely populated areas.
- ✓ Vegetation Density and Height Metrics as input variables to improve elevation predictions.
- ✓ GADM 2.0 Dataset ; collection of global administrative unit spatial boundaries used to assess bias and RMSE at smaller spatial scales.

2.2. Sociodemographic Data of the Study Area

Sociodemographic data necessary to assess the potential impacts of sea level rise on coastal communities were collected from several sources. Government agencies, such as national statistics offices, provided demographic and socioeconomic data specific to the region under study. Field surveys were also conducted to collect data directly from residents of coastal communities, including information on income, livelihoods, and existing infrastructure. In addition, previous studies, whether scientific, governmental, or conducted by local or international organizations, provided relevant data. Finally, online databases, such as those of the World Bank and the United Nations, provided socioeconomic data at the global, national, and regional levels.

2.3. Climate Records and Future Data

Historical climate data, including temperature, precipitation, and extreme events, were essential for assessing past and future climate trends. Data were obtained from the Agence Natonale de la Météorologie weather stations from 1981-2023, including reliable sources such as Climate Engine (NOAA/DRI/NIDIS https://app.climateengine.org/climateEngine), NASA POWER data, as well as the Climate Hazards Group InfraRed Precipitation with

Station data (CHIRPS) for past data. For future data, data from the Coopernicus website (https://cds.climate.copernicus.eu/#!/homen) were used for various CMIP5 Model Ensemble climate scenarios.

3. Data Analysis

3.1. Methods for Studying Climate Change

The analysis of climate change was carried out using various statistical and modeling methods and tools. These were used on time series of precipitation and temperature.

3.1.1. Data Criticism and Homogenization

Climate data were subjected to quality control consisting of detecting outliers and possible data duplications (Boyard-Analyse Micheau and Camberlin, 2015). Negative values, often marked by -99999, were first eliminated and subsequently reconstructed. Those missing on the time series were filled in by a subjective approach established on the analysis of double accumulations. This method is applied to stations whose monthly and annual data contain gaps. According to Beaulieu et al. (2005), it consists of making a linear regression on the cumulative values of the base series (v) as a function of the accumulated values of the reference series (x). A curve was produced for the pairs of points (x, y) on which the regression line is superimposed. If the series are homogeneous, the points are arranged randomly around the regression line (Merniz, 2021). The cumulative sums of the totals of the two neighboring stations, thus determined, follow a linear law around the first bisector, and any anomaly in the series of measurements of one of the two stations (or both) would cause a modification of the slope of this line (Rosenblatt, 1994). In the present study, only the stations with a discontinuity of the abrupt jump type were therefore corrected from the correction factor for a given month. The missing values calculated from the linear regression method, whose prediction equation is: a + bx and a and b are determined by the mathematical formulas:

$$a = \bar{y} - b\bar{x} \text{ et } b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2}$$

With x and y the average sample average (x_known) and average (y_known) x represents the observation whose value will be predicted (Koumassi, 2014); y_known represents the matrix or range of dependent data and x_known represents the matrix or range of independent data (Kodja, 2018). The temporary chronicles are thus filled. They were verified and validated before being considered for the analysis of the impact of climate variability on ecological and social systems.

3.1.2. Measures of Central Tendency

Central trends are measured by calculating the arithmetic mean. The arithmetic mean is used to analyze rainfall and thermometric regimes at the level of different stations. It is calculated for all stations (climatological, rainfall, and synoptic) considered in the present study and over the entire time series. It allows knowing the average monthly, seasonal, and annual values over the seventy-two years. It was calculated from the formula:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{1}(xi)$$

The arithmetic mean was used to characterize the average climatic state and to calculate the most significant dispersion indices (Doukpolo, 2014).

3.1.3. Estimation of Monthly, Seasonal, and Annual Rainfall Fields

The estimation of monthly, seasonal, and annual rainfall fields is done from the probabilistic method used by Drapeau (1990). This approach has already been used for several works (Baronetti et al., 2019 and Soubeyroux et al., 2019) in different regions of Benin and Africa. It has proven very effective in analyzing the spatio-temporal variation of rainfall in the Sudanian zone, using a homogenized database of average monthly and annual rainfall over seventy-two years. It is established from kriging, an interpolation method to estimate the values at non-sampled points by a combination of data. In addition, the precipitated water depths were appreciated by the Thiessen polygon method. This approach consisted of partitioning the geographical space, defining for each rainfall station Pi, a polygon of influence in such a way that each point of the polygon is closer to Pi than to any other station (Ouatiki, 2014). The perpendicular bisector to the segment joining these two neighboring points is drawn for each pair of rain gauges (Roux, 1996). The average precipitation over the domain is written as follows:

$$Pmoy = \frac{\sum_{i=1}^{n} Pi \times Si}{St}$$

With Pmoy: average rainfall over the domain, Pi: precipitation at the level of each station, Si: surface of each polygon, St: total surface of the Sudanian domain and n: number of stations. This approach made it possible to estimate the weighted values according to the weight of each rainfall station.

3.1.4. Dispersion Parameters and Standardized Anomalies

The dispersion parameters make it possible to indicate by how much the values of a distribution could generally deviate from the central reference value (Nouaceur, 2015). They are evaluated from the calculation of the standard deviation. Indeed, the standard deviation (σ) is determined by calculating the square root of the variance (V). It is expressed by the equation:

$$\sigma(x) = \sqrt{V}$$

The standard deviation is an excellent indicator of climate variability and change. It made it possible to calculate the reduced centered deviations of rainfall, temperatures, and aridity at the monthly time step. This analysis served to better analyze the frequency of extreme climatic events during the last seventy-two years in the Sudanian zone. It was done on each station and using the method of standardized indices or reduced centered anomalies proposed by WMO (2009), adopted by Bodian (2014) and Totin Vodounon et al. (2019, p. 279). Noted IAC, they express the standardized anomalies and are calculated by the formula:

$$IAC = \frac{Pi - Pm}{\sigma}$$

with: Pi, variable studied for a year, Pm and σ, respectively average and standard deviation of the climatic series over the study period. These indices were used to determine the years marked by a surplus or a deficit and consequently the response of the state of the surface in the domain of the Sudanian climate in Benin. The interpretation grid of the WMO (2012), used by Adigbégnon (2023) is used to determine the surplus, average and deficit years (table1).

Table 1: Interpretation grid of the reduced centered anomalies of precipitation.

Anomaly Indices	**Year Characteristic**
2,0 and more	Extremely wet
de 1,5 à 1,99	Very wet
de 1,0 à 1,49	Moderately wet
de -0,99 à 0,99	Close to normal
de -1,0 à -1,49	Moderately dry
de -1,5 à -1,99	Very dry
-2 and less	Extremely dry

Source: World Meteorological Organization (WMO), 2012, p. 5 and M. Adigbégnon, 2023, p. 20

The calculation of these indices was associated with the study of detection of stationarity rupture in the time series.

3.1.5. Detection of Stationarity Rupture in Time Series

The Khronostat 1.01 software, developed by the Mixed Research Unit (UMR 5569) of the HydroSciences Montpellier laboratory (Kodja et al., 2020), was used for the detection of stationarity rupture of rainfall series. The Pettitt and Buishand homogeneity tests (Diallo et al., 2020) are applied to detect stationarity rupture in the climate series. The principle of the Pettit test is as follows: Let Xt, t=1,2,…n be an element of the series. Let Ut = 2Wt - t(n+1) with Wt = ∑ Rj (j=1,2,….t); Rj being the rank of the element Xt in a series ranked in ascending order and Ut, the test index (Chédé, 2012). The absence of rupture in a series Xi of size N generates the null hypothesis H0. The implementation of this test assumes that for any instant t between 1 and N, the time series xi, i=1,t and xj, j=t+1, N belong to the same population (Totin Vodounon, 2010). The variable to be tested is the maximum in absolute value of the variable U t, N defined by:

$$\mathrm{U_{t,N}} = \sum_{\mathrm{i=1}}^{\mathrm{t}} . \sum_{\mathrm{j=t+1}}^{\mathrm{N}} \mathrm{D_{ij}}$$

Where Dij = sgn( )xi - x j with sgn(Z) =1 if Z > 0; 0 if Z = 0 and -1 if Z < 0. Let KN be the variable defined by the maximum in absolute value of U , Nt for t varying from 1 to N-1 . If K denotes the value of KN taken on the series studied, under the null hypothesis, the probability of exceeding the value is given approximately (Doukpolo, 2014) by:

$$\mathrm{Prob}(\mathrm{K_n} > K) \approx 2_{\mathrm{exp}}(-6\mathrm{K}^2/(\mathrm{N}^3 + \mathrm{N}^2))$$

For a risk a of given first species, if Prob(Kn > K) is less than a, the null hypothesis is rejected. This test is known for its performance and robustness. These tests were supplemented by the Bayesian method of Lee and Heghinian and Hubert segmentation (Essalek and Nahli, 2020) which propose a parametric approach whose application on a series requires a normal distribution of the values of the latter. According to Kodja (2018), the Bayesian method of Lee and Heghinian makes the hypothesis of a rupture on average at an unknown instant. The a priori distribution of the instant of the rupture is uniform, and given this information and the data, the method creates a probability distribution a posteriori of the instant of the rupture. As for the Hubert segmentation method, it serves to highlight the multiple variations that have occurred in the climate data series. This method makes it possible to cut the series into m segments (m>1) so that the average value calculated for the whole segment is differently significant from the average value of the nearby segment (s).

3.1.6. Study of the Direction of Climate Variations

The variation of the different climatic parameters studied was analyzed from the slope coefficient of the linear regression lines of equation y = ax+b. The a represents the variation indicator whose positive (+) or negative (-) sign reflects respectively an upward or downward trend in time x and b denotes a constant. This coefficient is used to appreciate the direction of climate variations in the Sudanian zone in Benin. Following stationarity rupture tests to identify the year of rupture, the average values of the sub-periods were calculated in order to express the rate of variation. Indeed, this rate was calculated from the formulas:

$$\mathrm{Txv} = 100.\left(\frac{\overline{\mathrm{X2}}}{\overline{\mathrm{X1}}} - 1\right) \text{ pour les précipitations}$$

With X1 and X2 respectively average of the periods before and after the rupture. These two equations are used to calculate the statistical significance of the general trends.

3.1.7. Method for Calculating Climatic Aggressiveness with the Fournier Index

The Fournier index (FI) is a measure of climatic aggressiveness based on the intensity of precipitation and its role in water erosion. It was proposed by Fournier (1960) and was later modified by Arnoldus (1980) to refine the assessment of the erosive potential of precipitation. The simple Fournier index (FI) is defined by the relation:

$$FI = \frac{p_{max}^{2}}{P_{totale}}$$

Where: Pmax denotes the maximum monthly precipitation (mm) and Ptotal represents total annual precipitation (mm). The higher the FI, the more precipitation is concentrated over a short period, thus increasing the erodibility of the soils (Panagos, et al., 2015). A low FI means a more homogeneous distribution of precipitation and a lower risk of erosion (Renard et al., 1997). Table (2).

Table 2: presents the classification of the Fourni index.

FI (mm)	Precipitation Erosivity Degree
< 60	Very low erosivity 🌿
60 - 90	Low erosivity 🌱
90 - 120	Medium erosivity 🍃
120 - 160	High erosivity 🌧
> 160	Very high erosivity ⛈

source: Fournier (1960) and Arnoldus (1980)

3.2.Methodology for Analyzing Coastal Erosion in Pointe-Noire

Coastal erosion in Pointe-Noire is influenced by current dynamics, sea level rise, and anthropogenic activities. This methodology aims to assess the evolution of the coastline, the hydrodynamic processes involved, and future impacts using quantitative indicators and mathematical models.

3.2.1. Analysis of Coastline Evolution

3.2.1.1. Coastline Extraction

Coastline extraction is an essential step for analyzing the evolution of coastal erosion in Pointe-Noire. This section details the approaches commonly used and the associated tools.

3.2.1.1.1. Segmentation by Spectral Index

Spectral indices improve the distinction between water and land by exploiting the spectral bands of satellite images. Among the indices calculated are the Normalized Difference Water Index (NDWI) and the Modified Normalized Difference Water Index (MNDWI). Indeed, the Normalized Difference Water Index (NDWI) is a spectral index to detect the presence of water by exploiting the reflection properties of water and land surfaces in different wavelengths. The NDWI was introduced by McFeeters (1996) and is calculated from the green (GG) and near-infrared (NIRNIR) bands of a satellite image. It is expressed by the formula:

$$NDWI = \frac{(G - NIR)}{(G + NIR)}$$

Where: G denotes the reflectance of the green band and NIR represents the reflectance of the near-infrared band. According to Xu (2006), the NDWI varies between -1 and 1. Positive values close to 1: generally correspond to water bodies and negative values or close to 0: Correspond to dry soils, urban areas, and vegetation. The NDWI is effective for detecting water bodies but may include certain reflective built surfaces (Thieler et al, 2009). In addition, some built surfaces and wet soils may be wrongly classified as water. To overcome this problem, Xu (2006) proposed a variant of the NDWI: the MNDWI (Modified Normalized Difference Water Index), which uses the middle infrared band (MIRMIR or SWIR) instead of the NIR. The Modified Normalized Difference Water Index (MNDWI) was therefore introduced by Xu (2006) as an improvement of the NDWI (McFeeters, 1996). Its main objective is to better distinguish water bodies by reducing errors related to urban surfaces and wet soils. The MNDWI is defined by the following relation:

$$NDWI = \frac{(G - MIR)}{(G + MIR)}$$

where: G represents the reflectance of the green band and MIR corresponds to the reflectance of the middle infrared band (SWIR - Shortwave Infrared). Unlike the NDWI, which uses the near-infrared band (NIR), the MNDWI exploits the middle infrared band (MIR/SWIR), which improves the separation between aquatic surfaces and urban infrastructure.

3.2.1.1.2. Identification of the Coastline with DSAS

- ✓ **Presentation of DSAS**

The analysis of coastline evolution is essential to understand the dynamics of erosion and accretion in coastal areas such as Pointe-Noire. The Digital Shoreline Analysis System (DSAS) tool, developed by Thieler et al. (2009) and integrated into ArcGIS, allows this analysis to be carried out rigorously. The DSAS (Digital Shoreline Analysis System) is an ArcGIS extension that allows measuring and quantifying coastline changes from a series of shorelines from satellite images, GPS surveys, or old maps. It made it possible to generate transects perpendicular to the shoreline to follow spatial and temporal variations; to calculate the rate of erosion and accretion of the coastline at different periods; to produce robust statistics on coastal evolution and to integrate several sources of geospatial data (historical maps, satellite images, field surveys).

- ✓ **Definition of the Reference Coastline**

The shoreline must be normalized and harmonized to ensure a correct comparison between different periods. The reference takes into account the limit of high waters observed on satellite images; the coastal vegetation line and the coastline calculated by spectral indices (NDWI, MNDWI).

- ✓ **Creation of a Transect Network**

As part of the coastline analysis with DSAS (Digital Shoreline Analysis System), the generation of transects is a key step. These transects are used to measure changes in shoreline position over time. Once the coastlines are imported into DSAS, the tool generates transects perpendicular to the shoreline at regular intervals; the transects were measured from the variations of the coastline over time and the DSAS parameters were configured. This configuration takes into account a space of 50 m between the transects over a length of 200 m. These measurements were sufficient to cover all the shorelines analyzed.

3.2.2. Calculation of Coastline Change Rates with DSAS

The Digital Shoreline Analysis System (DSAS) made it possible to analyze the variations of the coastline at Pointe Noire thanks to different methods of calculating the change rates. One of the simplest and most commonly used methods is the End Point Rate (EPR).

3.2.2.1. Definition and Formula of the End Point Rate (EPR)

The End Point Rate (EPR) is a simple method to estimate the rate of retreat or advance of the coastline between two dates (Fenster et al., 2001). It is obtained by the equation:

$$EPR = \frac{d}{t}$$

where: d is the distance between the first and last position of the coastline (in meters) and t is the duration between the two readings (in years). According to Crowell et al. (1991), if EPR is negative, the coast recedes therefore there is erosion. On the other hand, if EPR is positive, the coast advances and therefore there is accretion. In DSAS, the "End Point Rate (EPR)" is obtained from the mathematical formula used by Crowell et al. (1991) and Fenster et al. (2001) which is expressed by:

$$EPR = \frac{d_{final} - d_{initial}}{t_{final} - t_{initial}}$$

The results from DSAS are exported in the form maps with the change rates for each transect for complementary analyses.

3.3. Methodology for Sea Level Rise and Coastal Flood Risk Analysis in CoastalDEM v3.0

The methodology employed in CoastalDEM v3.0 to analyze sea level rise and coastal flood risk closely mirrors the approach developed by S. A. Kulp and B. H. Strauss. It leverages a sophisticated combination of advanced data sources and a convolutional neural network (CNN) to create a high-accuracy global coastal digital elevation model (DEM). The key aspects of this methodology are:

3.3.1. Base Elevation Model Fusion:

Instead of relying on a single base elevation model like NASADEM used in CoastalDEM v2.1, v3.0 fuses multiple global DEMs. This approach mitigates spatially-autocorrelated vertical errors inherent in any single source and leverages the individual strengths of each dataset.

3.3.2. Convolutional Neural Network (CNN):

A CNN architecture is employed to predict and correct errors present in the underlying global elevation models. CNNs are specifically designed for image-based tasks, making them well-suited for processing the gridded spatial data used in this application.

3.3.3. Training Data:

The primary training dataset was the latest version (v6) of NASA's ICESat-2 mission data. ICESat-2 provides space-based lidar measurements of global elevation, offering a valuable ground truth source.

A building removal process was applied to ICESat-2 data in densely populated areas (over 10,000 people per square kilometer) to improve accuracy in urban environments. This involved a sliding percentile function to estimate terrain height beneath vegetation and buildings.

3.3.4. Input Variables:

CoastalDEM v3.0 incorporates a diverse set of input variables to enhance prediction accuracy, including:

- ☑ Elevation data from multiple base DEMs
- ☑ Population density data
- ☑ Vegetation density and height metrics

In total, CoastalDEM v3.0 uses 10 independent input datasets.

3.3.5. Independent Validation:

To ensure the model's robustness and prevent overfitting, CoastalDEM v3.0 was validated against independent, high-accuracy elevation data derived from airborne lidar. These lidar datasets, sourced from NOAA (US coastline) and Geospace Australia (Australian coastlines), provided a reliable benchmark for assessing the model's performance.

CHAPTER IV: RESULTS AND DISCUSSION

This chapter presents and discusses the findings of our investigation into climate change impacts and coastal dynamics in the Pointe-Noire region. The results encompass an analysis of historical climate trends, future projections, and the multifaceted consequences of coastal erosion and sea-level rise, providing a comprehensive understanding of the challenges and potential future scenarios facing this critical coastal zone.

4.1.RESULTS

Part I: Analyze climate change and its consequences in the Pointe Noire region.

4.1.1. Study of Climate Change in Pointe-Noire and the Loango Region

4.1.1.1.Monthly, Seasonal, and Annual Rainfall Fields

Rainfall, a primary climate factor, is unevenly distributed in the Pointe-Noire and Loango region. Rainfall depths range from 25.59 mm in March to 231.76 mm in August. The lowest rainfall amounts were recorded in December-January (2.32-2.47 mm). The Sudanian zone in Benin exhibits a unimodal rainfall regime with an annual average of 1083.72 ±113.30 mm, reaching its peak in August (231.50 mm) (Figure 3).

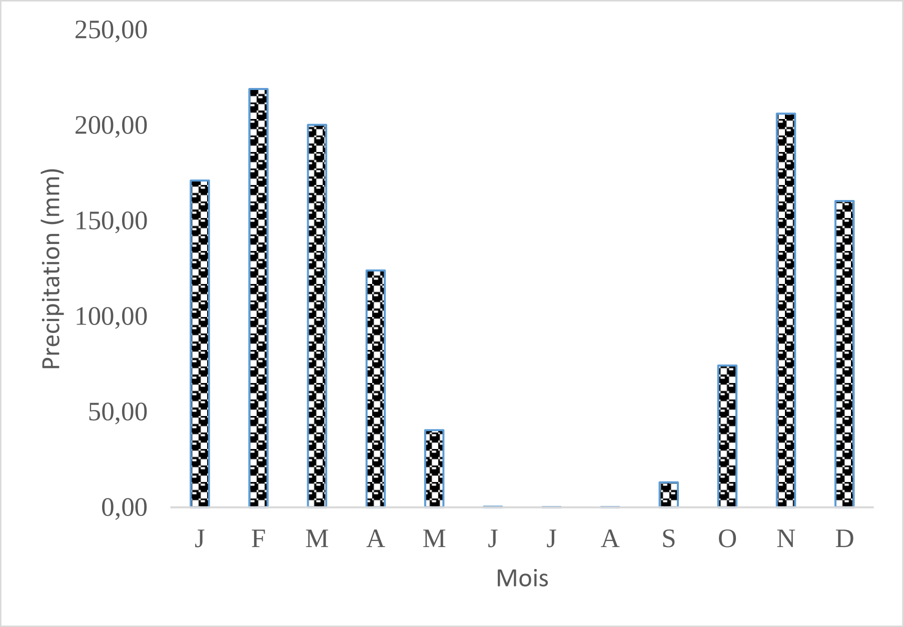

Figure 6:Average (a) and extreme seasonal (b) rainfall regimes in the regionalized Pointe Noire and Loango region (1981-2023).

The highest rainfall is observed in February (218.98 mm), March (200.32 mm), and November (206.21 mm), suggesting a distinct rainy season. A gradual decrease in rainfall is visible between April and August, with an absolute minimum in July and August (0.01 mm in August), indicating a well-defined dry season. Rainfall begins to increase in September and reaches a peak in October-November. This distribution is typical of a tropical climate with alternating dry and rainy seasons. The rainy season appears bimodal, with a first peak in March-April and a second in October-November. The potential impacts of this seasonal variation in rainfall are observable on water resources, activities in urban areas, and soil erosion. The months of June to August are critical for water management and agricultural activities requiring irrigation. High rainfall in February-March and October-November can lead to risks of flooding or soil erosion. This rainfall variability is a key factor to consider for agriculture, water resource management, and adaptation to climate change.

4.1.1.2.Interannual Rainfall Variability in Pointe-Noire

The SPI index is used to assess rainfall anomalies, highlighting periods of drought and excessive humidity (Fig.7).

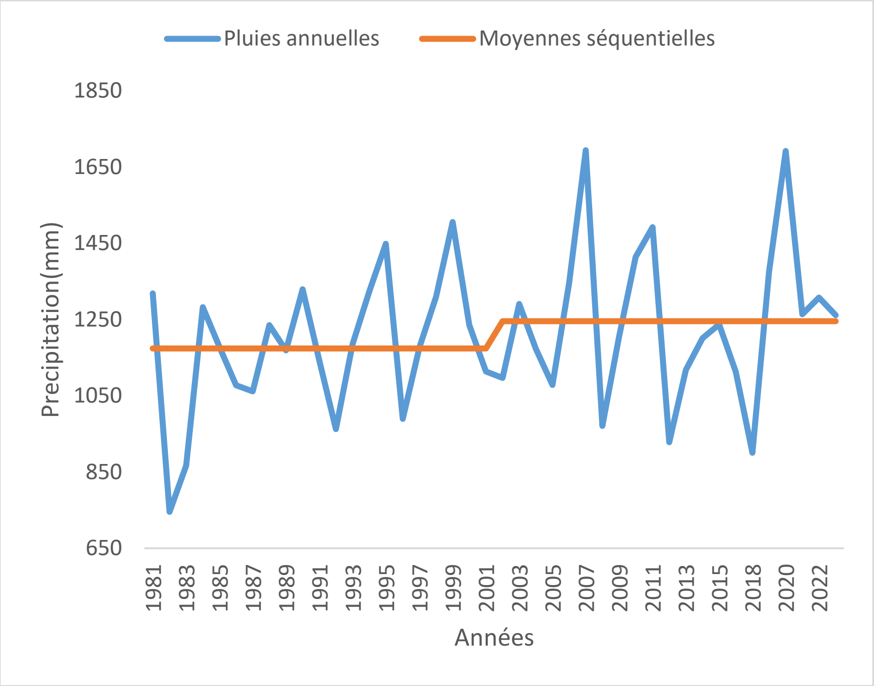

Figure 7: Interannual Rainfall Variability in Pointe-Noire.

The data presented show the evolution of annual rainfall (in mm) over several decades, compared to sequential averages. The sequential average evolves slightly between 1173.95 mm (1981-2001) and 1245.44 mm (2002-2023), indicating a slight increase in average rainfall over the recent period. Strong fluctuations are visible from year to year, with very dry years (1982: 745.39 mm; 2012: 928.36 mm; 2018: 900.12 mm) and very wet years (2007: 1693.84 mm; 2020: 1691.46 mm). The strong variations in rainfall have a direct impact on agricultural yields, with droughts potentially reducing production and excess water potentially causing flooding and soil erosion. Rainfall shows cycles of drought and humidity with an alternation of deficit and surplus years. Since 2002, several years have recorded above-average rainfall (2007, 2010, 2011, 2020). However, some years show a marked deficit, which underlines the importance of climate variability. The more frequent alternation between dry and wet years could be a sign of an intensification of climate extremes, requiring adaptation strategies.

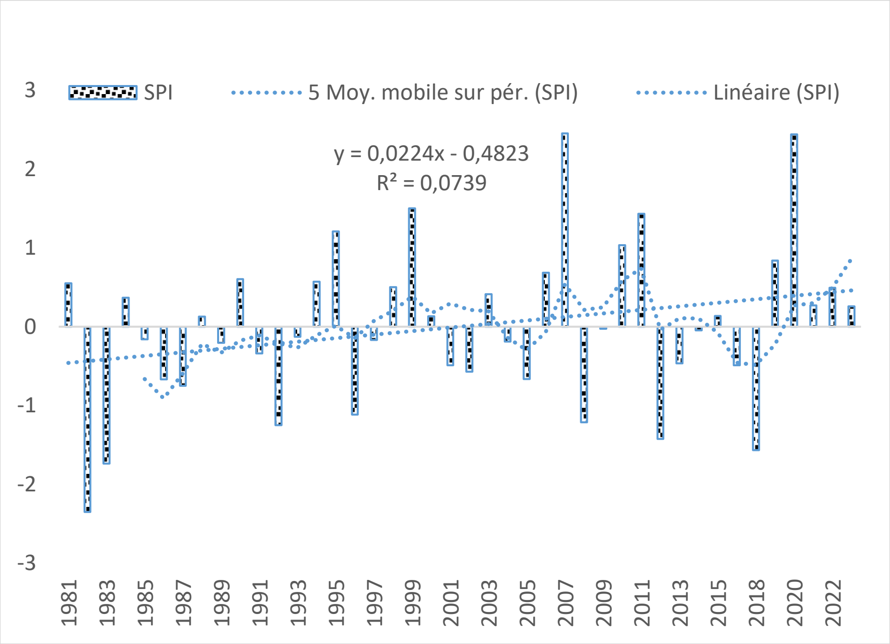

Figure 8:Reduced centered deviations of rainfall between 1981 and 2023 in Pointe Noire.

The analysis of (Fig.8) shows an alternation of dry and wet periods is visible, indicating a marked climate variability. A succession of moderate droughts is observed after 2012, suggesting a possible modification of the rainfall regime. The SPI remains positive in 2021, 2022 and 2023, which indicates overall surplus rainfall in recent years. In addition, two major periods were observed between 1981 and 2023. These include a period of marked drought (SPI < -1), during which the years 1982 (-2.35) and 1983 (-1.74) experienced a prolonged severe drought; 1992 (-1.25), 1996 (-1.11) and 2012 (-1.42) recorded notable water deficits and 2018 (-1.57), the water stress was very significant. The droughts of the 1980s and 1990s may have impacted agricultural production. Very humid periods can also be problematic (flooding, soil erosion). And a second period the rainfall processes are very intense (SPI > 1) especially in 1995 (1.21) and 1999 (1.50) which were very wet years; in 2007 (2.45) and 2020 (2.44) where the rainfall maxima were very exceptional and in 2010 (1.03) and 2011 (1.43) marked by humid sequences. The alternation of droughts and excess water could intensify with global warming, requiring adaptation strategies.

4.1.1.3.Stationarity Rupture, Variations and Rainfall Trends

The rainfall series in the Pointe-Noire sector experienced a break in 1983 with a 95% confidence level (Figure 9).

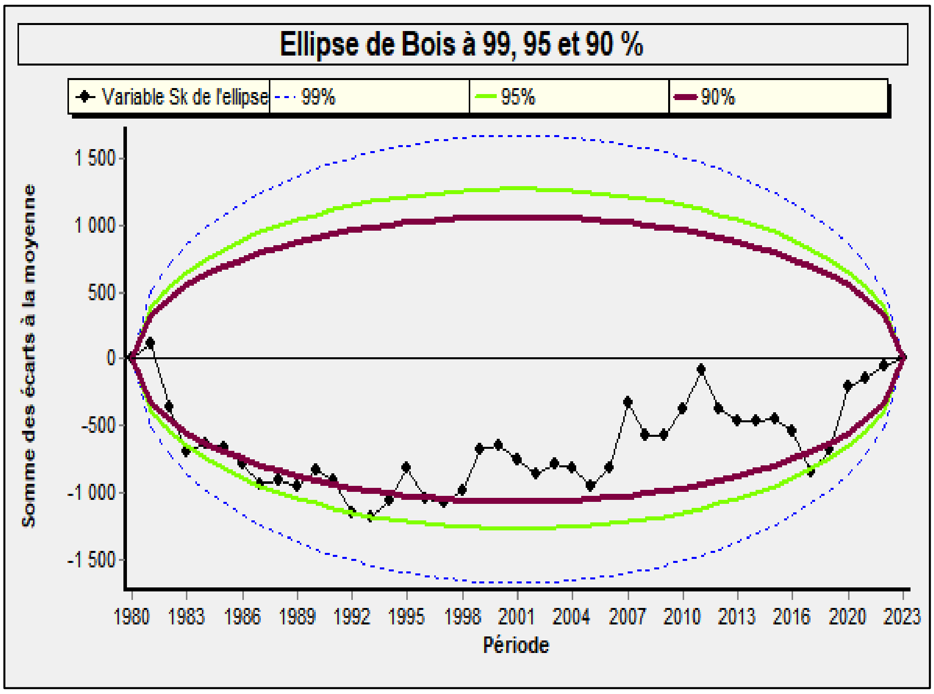

Figure 9:Stationarity rupture (1981-2023) on rainfall: Wood Ellipse.

By applying the Buishand rupture test to the average data, a significant rupture emerges at the 95% threshold and therefore the Lee and Heghinian test makes it possible to highlight the probable year of this rupture in 1983. The Pettitt test shows that the change observed in the evolution of average rainfall in the Sudanian zone began since 1983 and has further strengthened since 1993 as shown in Figure (10).

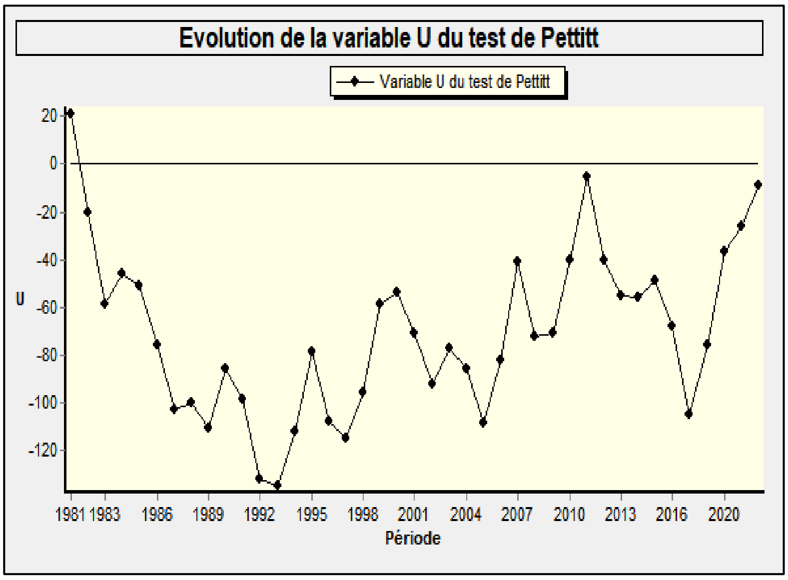

Figure 10: Stationarity rupture (1981-2023) on rainfall: "A posteriori" probability density of the position of a change.

This shows that the study area is marked by a considerable decrease in post-rupture rainfall thus affecting both rainfall regimes but also its ecological and societal systems. The long years of drought have caused the depletion of groundwater leading to hydrological deficits more accentuated than rainfall deficits (Zare, 2015). In addition, Hubert's segmentation (significance of the Scheffé test: 1%) shows that the rains in the Sudanian area experienced two ruptures during the period of 1981-2023.

4.1.1.4.Analysis of Temperature Evolution in Pointe-Noire (1981-2023)

The analysis of annual temperatures recorded in Pointe-Noire between 1981 and 2023 reveals an overall upward trend, suggesting a progressive climate warming over the period studied as shown in Figure ().

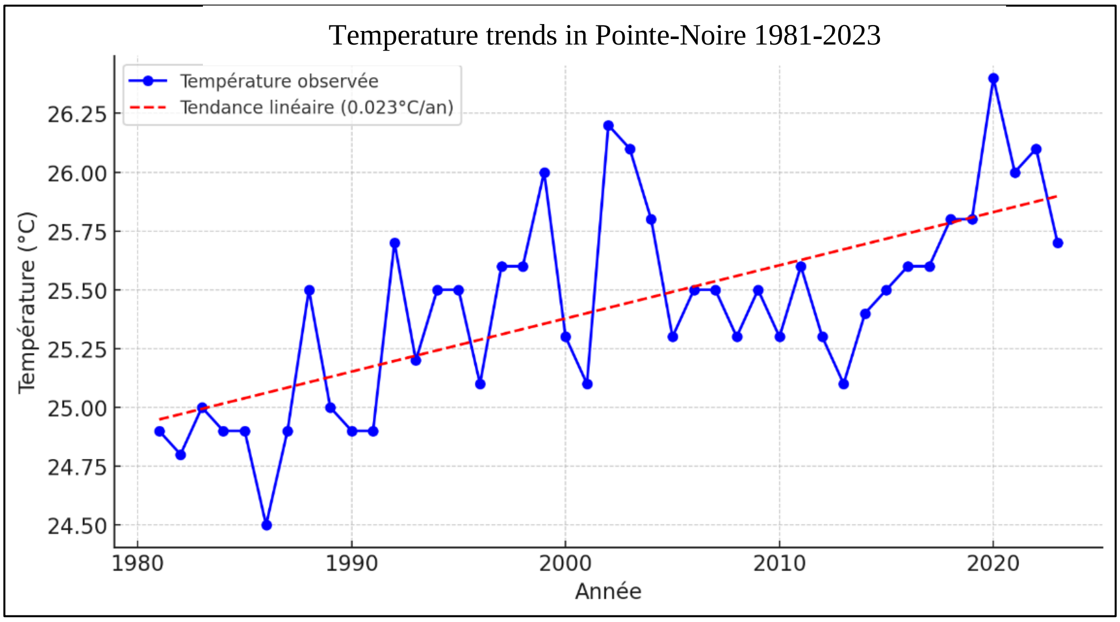

Figure 11: Interannual variability of average temperatures in Pointe-Noire (1981-2023).

The analysis of Figure (11) shows an average temperature increase trend of +0.023°C per year. This trend is characteristic of a progressive climate warming in Pointe-Noire. Fluctuations from year to year may be related to climatic events such as El Niño/La Niña and local variations. In addition, the rise in temperatures has had impacts in Pointe-Noire on the loss of biodiversity, the degradation of agricultural resources and water resources. It has led to the strengthening of coastal erosion, accentuated by sea level rise and extreme weather conditions. The increase in temperatures could be linked to the impact of climate change, including the effect of urbanization, deforestation, and the increase in greenhouse gases (GHG). The annual variations in temperatures depend on the monthly variations as presented by Figure (12).

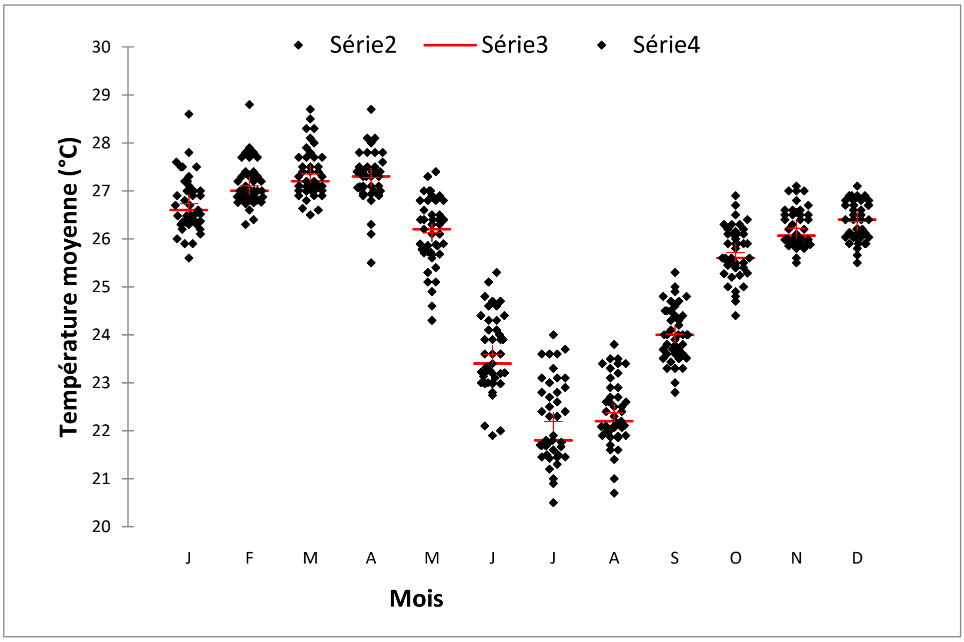

Figure 12: Thermometric regime and extremes (minima and maxima).

The minimum, maximum and average temperatures vary significantly during the year. Thus, in the Pointe-Noire region, there is a hot and humid season from January to May where average temperatures are relatively high and vary between 26.7 °C and 27.35 °C. During this period, the months of March and April record the highest temperatures (27.7°C) during the year. On the other hand, the period from June to September is essentially the coolest and driest with minimum temperatures that drop to 21.55 °C in July. In addition, there is a period of return of heat between October and December, marked by temperatures reaching 26.36°C on average in December. This analysis confirms a trend of climate warming in Pointe-Noire, with temperatures increasing progressively since the 1990s. It is therefore imperative to continue climate monitoring and to develop adaptation strategies to these developments.

4.1.2. Impact of Climate Change on Erosion in Pointe-Noire

4.1.2.1.Climatic aggressiveness

Climatic aggressiveness refers to the intensification of extreme weather events such as intense rainfall, prolonged droughts, violent winds, and sea level rise. In Pointe-Noire and Loango, located on the Atlantic coast of Congo, this climatic aggressiveness manifests itself through several worrying factors.

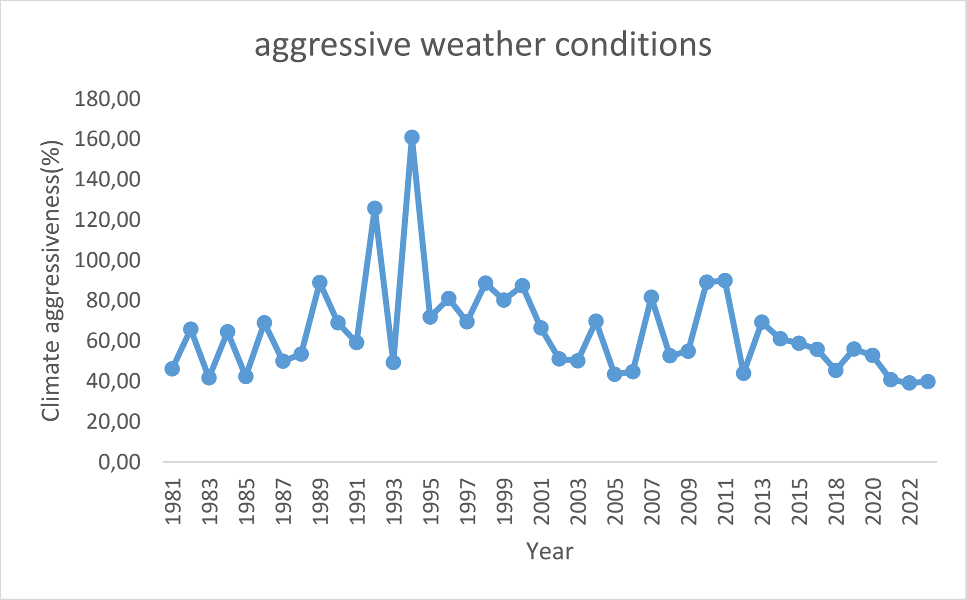

Figure 13: Interannual variation of climate aggressiveness in Pointe Noire from 1981 to 2023

Pointe-Noire and Loango have experienced irregular rainfall, with periods of heavy rainfall that can cause urban flooding and seasonal droughts affecting agriculture and water resources. The alternation between heavy rainfall and periods of drought accentuates soil erosion and ecosystem degradation. Sea level rise is a major threat to the coastal areas of Pointe-Noire and Loango, increasing coastal erosion and threatening port and tourist infrastructure. The accentuation of storms and ocean swells favors the retreat of the coastline and the salinization of agricultural land and groundwater. Episodes of strong winds are observed, impacting precarious housing and increasing the risks for fishing and maritime transport activities. These phenomena also aggravate soil erosion, particularly in deforested and urbanized areas. Climate aggressiveness in Pointe-Noire and Loango is a reality that requires urgent and adapted actions. Climate risk management, combined with adaptation strategies, will better protect populations and ecosystems from growing environmental challenges.

4.1.2.2.Erosive capacity

Erosion is a worrying phenomenon in Pointe-Noire and Loango, where climatic and anthropogenic factors exacerbate the degradation of soils and the coastline. The study of erosive power in these regions makes it possible to better understand the mechanisms at play and to identify adapted mitigation strategies.

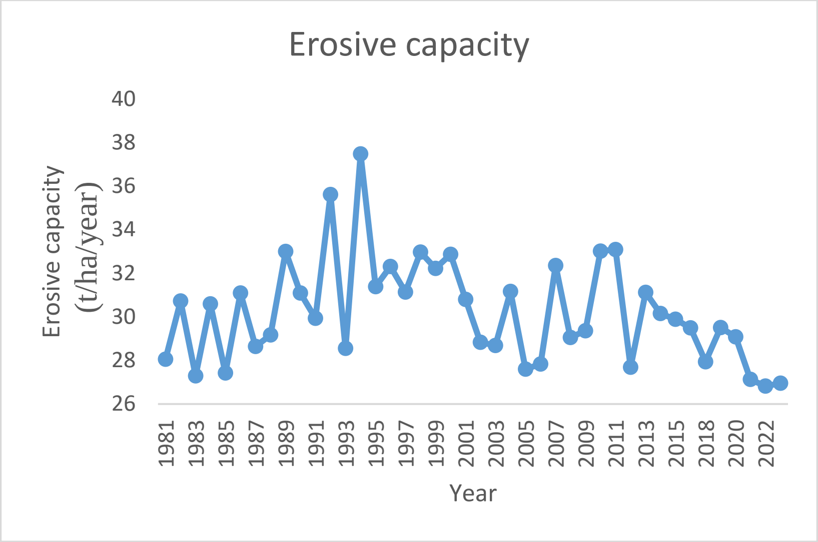

Figure 14: Evolution of erosive capacity in Pointe Noire between 1981 and 2023.

Heavy rains, particularly in the rainy season, lead to significant runoff, accentuating water erosion of soils. The climate aggressiveness index (based on the intensity and duration of rainfall) is high, contributing to the formation of ravines and the removal of fertile layers. Erosion in Pointe-Noire and Loango is a worrying phenomenon, exacerbated by extreme climatic conditions and unsustainable human activities. Effective management of erosive power requires an integrated approach combining ecosystem conservation, adapted infrastructure and community awareness.

4.1.2.3.Marine Pressure at the Pointe Noire Station between 1981 and 2023

The observation of monthly atmospheric pressure values reveals significant fluctuations throughout the year.

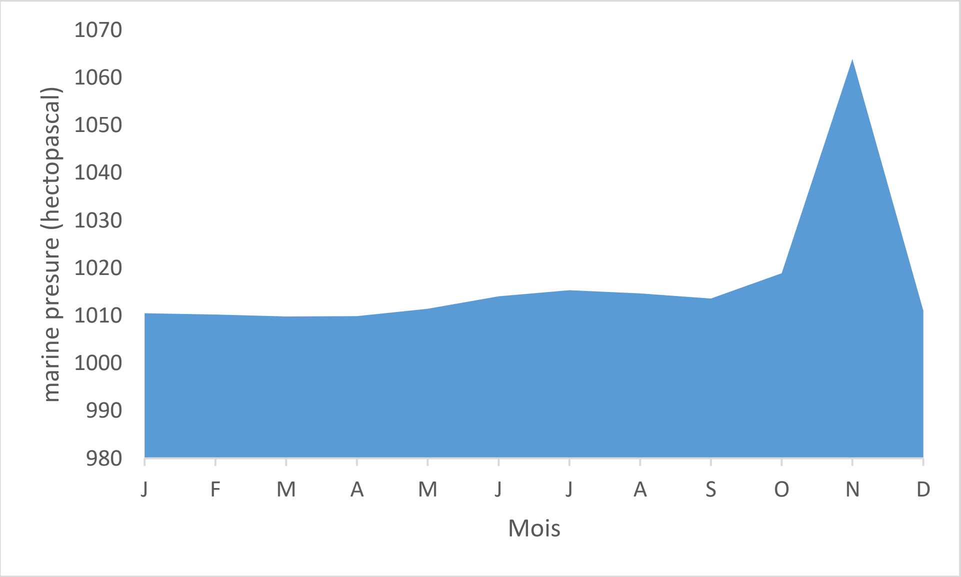

Figure 15: Monthly variation of marine pressure at the Pointe Noire station.

From January (1010.49 hPa) to April (1009.85 hPa), the pressure remains relatively low, indicating a more unstable period on the atmospheric level. This decrease could favor an increase in rainfall and climate instability. The pressure begins to increase from May (1011.41 hPa) and reaches a peak in October (1018.91 hPa). This trend could be related to the influence of subtropical anticyclones, which stabilize the atmosphere and reduce the probability of precipitation. The value of 1063.91 hPa in November seems abnormally high compared to the other months. It is possible that this value is a data entry error, a local anomaly, or an exceptional meteorological phenomenon requiring further analysis. After the high value of November, the pressure drops back to a more typical level in December.

The study of atmospheric pressure over several decades reveals interesting trends that can be related to local and global climate dynamics.

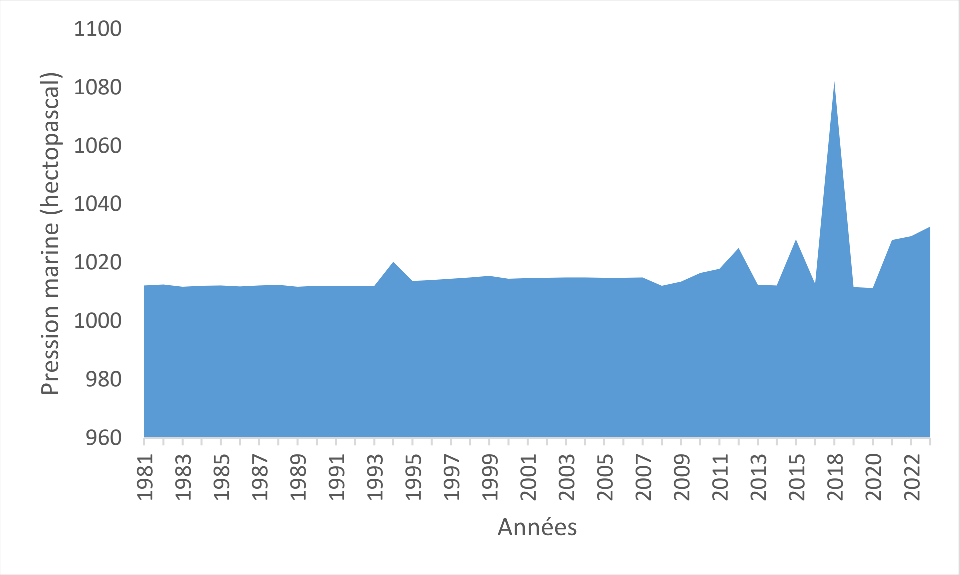

Figure 16: Interannual variability of marine pressure in Pointe Noire from 1981 to 2023.

The atmospheric pressure oscillates slightly around 1012 hPa, with minor variations. These fluctuations are normal and do not indicate marked climate changes. A clear increase is observed from 1994 (1020.26 hPa), with a pressure reaching 1015 hPa in 1999 and remaining above 1014 hPa until 2007. This trend could be linked to changes in regional atmospheric circulation or to influences from oceanic anomalies (e.g.: variations of the tropical Atlantic). More marked oscillations appear between 2008 and 2017, with an exceptional peak in 2015 (1027.87 hPa). These variations could be associated with major climatic events such as El Niño, which strongly influences atmospheric pressure and rainfall in Central Africa. An extremely high value of 1082 hPa in 2018 is suspicious and could be due to a measurement or entry error. However, from 2021, there is a marked increase with values reaching 1032 hPa in 2023, which is significantly higher than the averages of previous decades. This increase could be a sign of long-term climate changes affecting atmospheric circulation in the region. The recent rise in atmospheric pressure in Pointe-Noire and Loango is a potential signal of regional climate changes, requiring careful monitoring and further analysis to anticipate environmental and socio-economic impacts.

4.1.3. Climate Projection until 2050 Based on the Current Trend

4.1.3.1.Rainfall Projection until 2050 in Pointe-Noire

The analysis of historical rainfall data in Pointe-Noire shows interannual variability with episodes of high humidity and drier periods. A linear trend has been applied to the data to estimate future rainfall. Taking 2023 as a reference, the average rainfall is approximately 1305 mm/year. If the current trend continues, applying an annual growth of 4.5 mm, the rainfall would reach approximately 1425 mm/year in 2050.

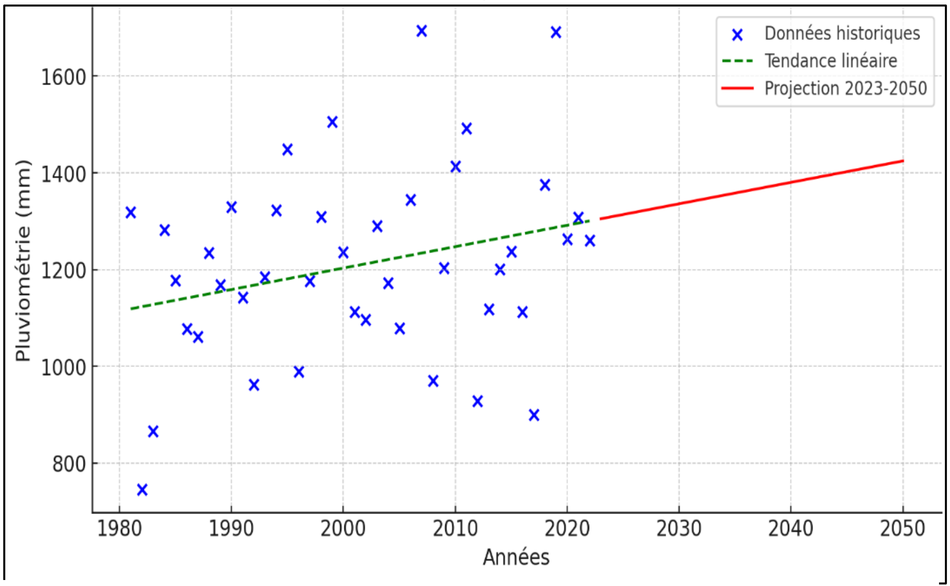

Figure 17: Projection of average precipitation in Pointe Noire between 1981 and 2050

The analysis of Figure (17) shows a linear trend shows a progressive increase in rainfall of approximately 4 to 5 mm per year. Thus, in 2023, the estimated rainfall is approximately 1305 mm. In 2050, the projection gives a value close to 1425 mm, an increase of approximately 120 mm over 27 years. The increase in rainfall could increase the risk of flooding, particularly in the rainy season. More abundant rainfall, combined with sea level rise, could accentuate the risks of coastal erosion and flooding in urban and rural areas. Indeed, the high interannual variability (very wet years followed by drier years) could destabilize agricultural and hydrological systems. It is essential to couple these projections with more detailed climate scenarios (RCP) to anticipate the evolution of rainfall depending on climate change (Figure18).

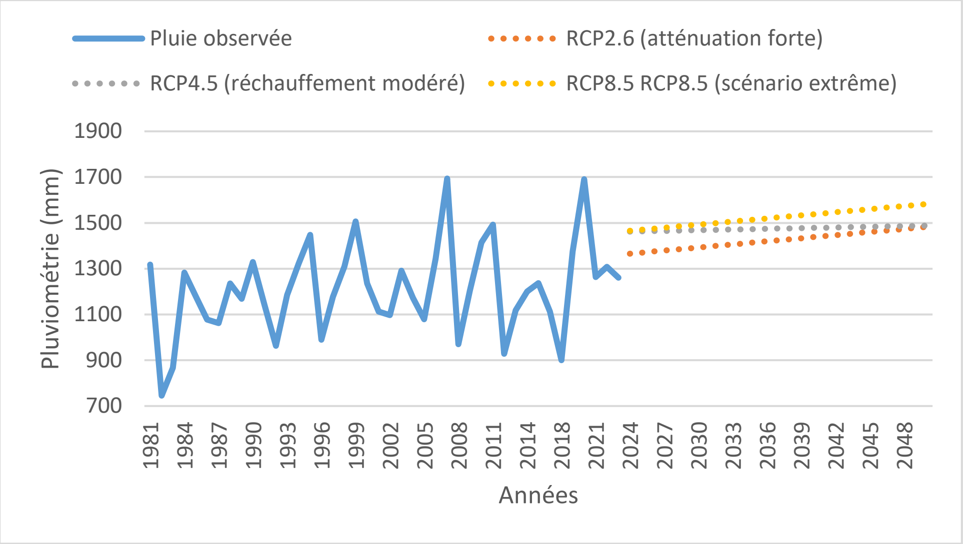

Figure 18:Projection of annual rainfall in Pointe Noire between 1981 and 2050

The projections of annual rainfall show an upward trend until 2050, with notable differences according to the IPCC climate scenarios (table).

Table 3: Projections for 2050 according to RCP scenarios

Scénarios	Projected rainfall in 2050 (°C)	Variation compared to 2023
RCP2.6 (strong climate policy)	1482,5 mm	≈ +121,5 mm
RCP4.5 (progressive stabilization)	1488 mm	≈ +227 mm
RCP8.5 (high emissions scenario)	1582,5 mm	≈ +321,5 mm

The results of the projections carried out show a moderate increase in rainfall of 1482.5 mm in 2050 (+121.5 mm compared to 2023) for the RCP2.6 scenario (strong mitigation). A moderate increase indicates effective management of greenhouse gas emissions. The increase in rainfall remains manageable, with limited impacts on the environment and agriculture. On the other hand, the RCP4.5 scenario (moderate warming) translates into a faster progression of annual rainfall with a value of 1488 mm in 2050 (+227 mm compared to 2023). The more marked increase in precipitation, potentially leading to an intensification of extreme events (flooding and erosion). Despite the trend of climate warming, the RCP8.5 scenario (extreme warming) presents an increase in annual rainfall in Pointe Noire characterized by very surplus values of 1582.5 mm in 2050 (+321.5 mm compared to 2023). In this context, increased risks of intense and prolonged precipitation; flooding, soil saturation and coastal erosion will be observed in the Pointe-Noire region.

4.1.3.2.Temperature Projection until 2050 in Pointe-Noire

The coefficient of variation (CV) of annual temperatures in Pointe-Noire is approximately 1.67%, indicating low interannual temperature variability. The projection of temperatures until 2050 shows an upward trend, following a linear regression based on data observed since 1981. If this trend continues, the average temperature could exceed 26.5°C by 2050, which shows a progressive warming.

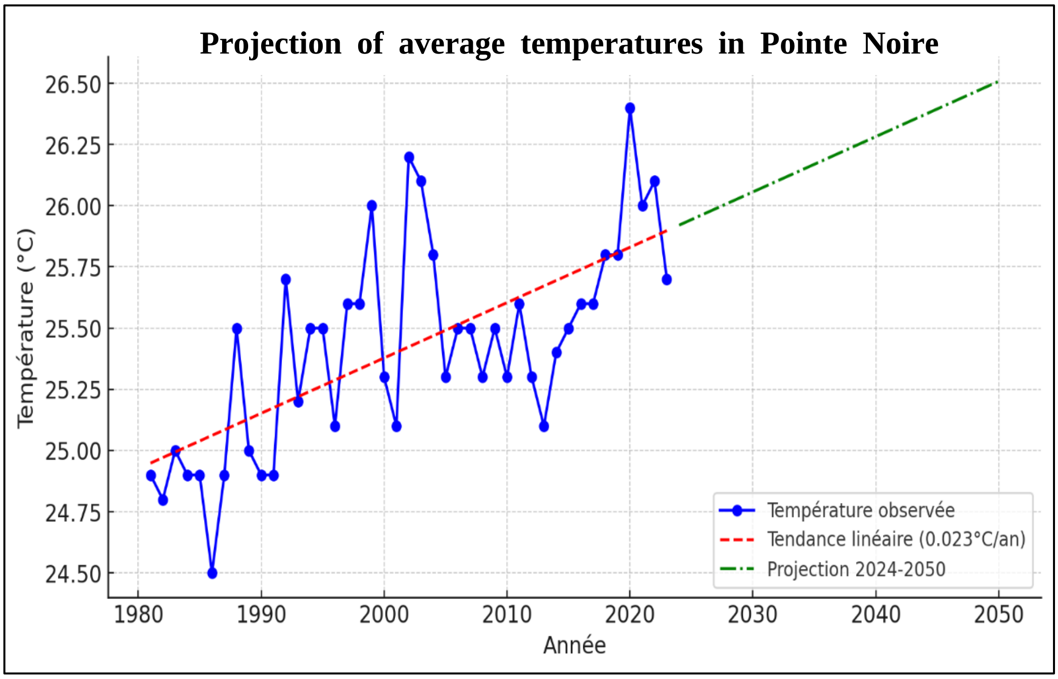

Figure 19: Projection of average temperatures in Pointe Noire between 1981 and 2050

These results highlight a relative stability of annual temperatures in Pointe-Noire with low variability (CV = 1.67%). The low annual variability shows a homogeneous climate trend without extreme fluctuations. The upward trend in temperatures is consistent with regional projections of the IPCC (2021) and the work of Nicholson (2018) on warming in Central Africa. However, the linear trend indicates a progressive increase in temperatures, reaching approximately 26.51°C in 2050, or +0.5°C compared to 2023. This increase could accentuate evaporation, modify rainfall regimes and increase the risks associated with coastal erosion and climate variability in the Pointe-Noire sector. Thus, the temperature projections for Pointe-Noire by 2050 show warming trends more or less marked according to greenhouse gas emission scenarios. These scenarios, based on the Representative Concentration Pathways (RCP), developed by the IPCC (IPCC, 2014) describe different possible trajectories depending on the climate policies put in place (figure).

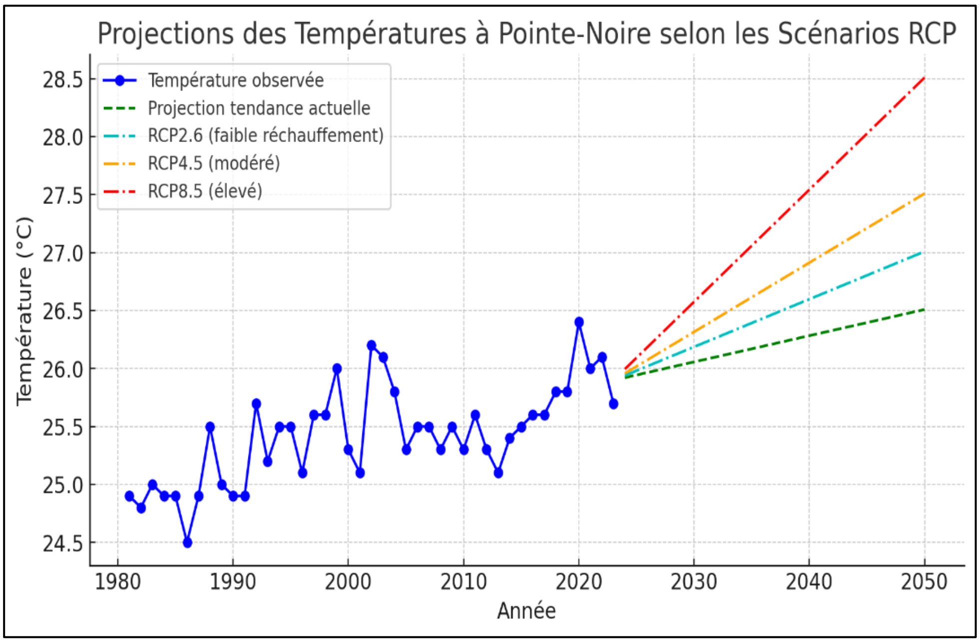

Figure 20: Projection of average temperatures in Pointe Noire between 1981 and 2050 according to RCPs

Historical data show a progressive trend of increasing temperatures in Pointe-Noire, with an annual average rising from approximately 24.9°C in 1981 to 26.0°C in 2023. This increase of +1.1°C in just over 40 years already reflects ongoing regional climate warming. Indeed, the increase in ocean temperatures leads to thermal expansion and the acceleration of polar ice melt, contributing to sea level rise. Pointe-Noire, being a coastal city, is particularly vulnerable to coastal erosion and the submergence of low-lying areas. With RCP8.5, rising sea levels could cause the disappearance of beaches, salinization of agricultural soils, and threaten port and residential infrastructure. Table () presents the possible temperatures in 2050 compared to 2023.

Table 4: Projections for 2050 according to RCP scenarios

Scénarios	Projected temperature in 2050 (°C)	Variation compared to 2023
RCP2.6 (strong climate policy)	26,24°C	≈ +0,24°C
RCP4.5 (progressive stabilization)	27,05°C	≈ +1,05°C
RCP8.5 (high emissions scenario)	28,40°C	≈ +2,40°C

The analysis of the table shows that if emission reduction measures are implemented on a global scale (RCP2.6), warming could be contained below +0.5°C by 2050, which would limit climate impacts. On the other hand, if emissions follow an intermediate scenario (RCP4.5), the temperature could increase by approximately +1.0°C, already significantly affecting local conditions. Moreover, in the event of uncontrolled emissions growth (RCP8.5), Pointe-Noire could experience warming of +2°C to +2.5°C by 2050, with severe consequences for the environment and populations. An increase of +1 to +2.5°C would increase the frequency and intensity of heat waves, affecting vulnerable populations (the elderly, children). A warmer climate can also promote more intense storms and irregular rainfall, increasing the risk of flooding and landslides.

Part II: Dynamics and Impacts of Coastal Erosion in Pointe-Noire

This section aims to examine the dynamics of coastal erosion in Pointe-Noire, relying on a diachronic approach and an analysis of socio-economic impacts. First, the historical evolution of the coastline will be traced to identify trends of retreat and accretion. Next, a mapping of areas that have experienced an advance of the coastline will allow a better understanding of the mechanisms of accretion. Finally, the sectors most affected by erosion will be studied, highlighting the factors responsible for this phenomenon as well as its consequences for local populations and infrastructure.

4.1.4. Historical Evolution of the Coastline

A result presents a comprehensive overview of coastal erosion patterns in Pointe-Noire, derived from our diachronic analysis of shoreline changes between 2000 and 2023. The map highlights the spatially variable nature of erosion across three distinct zones: the downtown and port area (Zone 1), the northern coastline (Zone 2), and the southern coastline (Zone 3). The colored lines represent historical shoreline positions, with the color gradient indicating the rate of retreat or growth, allowing for a visual assessment of erosion intensity and trends in each zone.

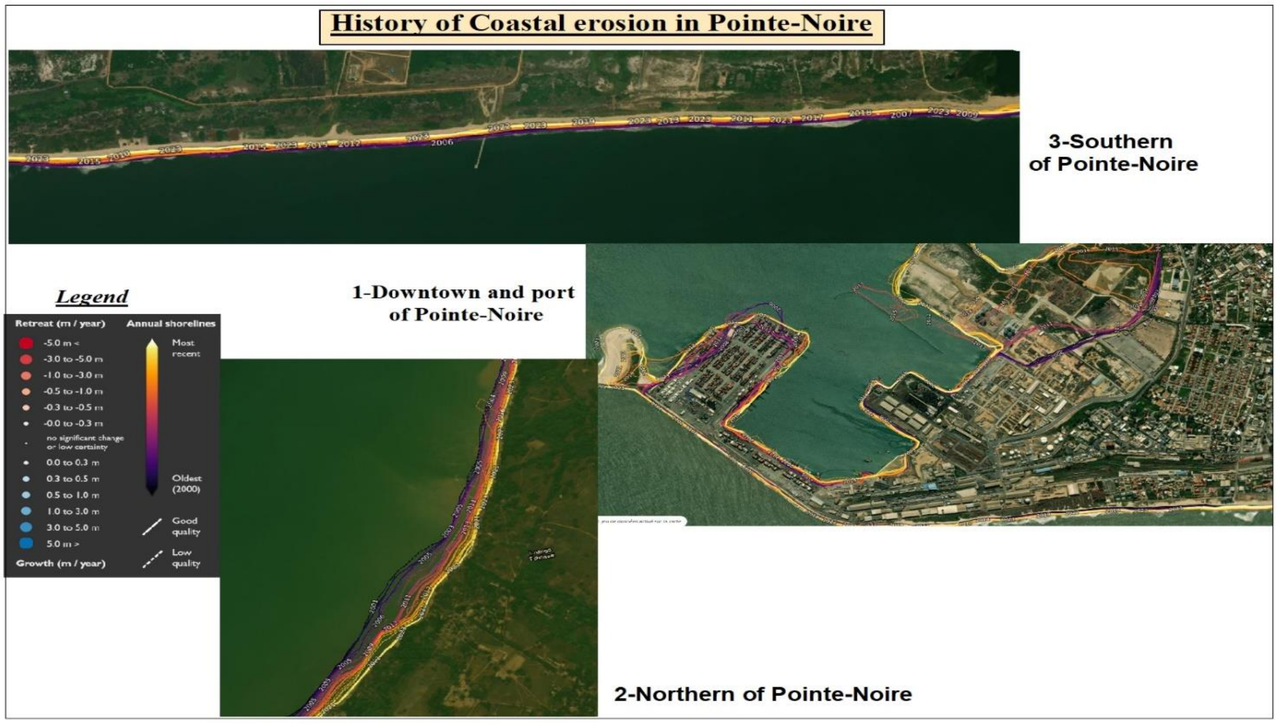

Figure 21: History of Coastline Erosion in Pointe-Noire

The diachronic analysis of the coastline in Pointe-Noire between 2000 and 2023 highlights differentiated erosion trends depending on the area, with notable impacts on the stability of the coastline and socio-economic activities. Zone 1 (City Center and Port) is the most vulnerable to erosion, particularly around port infrastructure. The analysis reveals a significant retreat of the coastline, already observable in 2000-2001. The superposition of the most recent coastline lines shows a correlation between port urbanization and erosion, probably accentuated by the intensity of industrial activities. Regarding Zone 2 (North of Pointe-Noire), erosion in this area is older and continues at a sustained pace. The coastline lines of the 2000s, located well back from the current coast, testify to a progressive erosion process over a long period. The presence of vast marshy plains and wetlands accentuates the vulnerability of the coastline to coastal retreat phenomena. Zone 3 (South of Pointe-Noire): The evolution of the coastline is more recent and less marked than in the other zones. Erosion seems more moderate, possibly due to more recent and less dense urban development. However, this relative stability could be threatened in the medium term with urban expansion and the impacts of climate change.

4.1.5. Coastal Accretion Areas: Processes and Implications in Pointe-Noire

This analysis focuses on areas of shoreline accretion identified within the downtown and port region of Pointe-Noire (Zone 1). While this zone is generally characterized by erosion, our analysis reveals localized areas of sediment accumulation, particularly along the northern edge of the port infrastructure. The map displays the rates of shoreline growth in meters per year, with values indicating the magnitude of accretion. These accretion zones are likely linked to port development activities, such as dredging and the construction of coastal structures, which have altered sediment transport patterns.

The results (Fig. highlight areas of coastal accretion, mainly located in the city center and port sector of Pointe-Noire, contrasting with the mostly erosive sectors. The most significant accretion is observed in the northern part of the port, with coastline growth rates reaching 49.3 ± 9.4 m/year and 46.5 ± 7.5 m/year, suggesting a substantial sedimentary input. Secondary accretion zones, although of lesser magnitude (0.5 to 1.7 m/year), are also identified inside the port and along the coast to the south. These processes seem intimately linked to port development and expansion activities, including dredging operations that generate large volumes of redistributed sediments, as well as the construction of new structures such as dikes and breakwaters, modifying local hydro-sedimentary dynamics and promoting sediment trapping. Although potentially contributory, fluvial sediment inputs seem to play a secondary role in these accretion dynamics.

Figure 22: Shoreline accretion in Pointe-Noire Region.

4.1.6. Areas of Coastal Retreat

This result illustrates the areas of shoreline retreat observed along the northern (Zone 2) and southern (Zone 3) coastlines of Pointe-Noire. The map displays the rates of shoreline retreat in meters per year, with negative values indicating land loss due to erosion. The intensity of erosion varies along the coastline, with certain areas experiencing more significant retreat than others. These erosion patterns are influenced by a combination of natural factors, such as wave action and sediment supply, and anthropogenic factors, such as coastal development and mangrove deforestation.

The model highlights areas of coastal retreat, where the coastline has receded inland, mainly to the north and south of Pointe-Noire, thus contrasting with the accretion zones observed in the port area, and highlighting the need for an in-depth analysis. In the northern zone, the retreat is particularly visible, with retreat values of up to -1.9 m/year (± 0.3 m) and -2.5 m/year (± 0.4 m), suggesting significant erosion, especially near the mouth of a watercourse or a lagoon area, while in the southern zone, the retreat is more uniform, with retreat values of up to -1.5 m/year (± 0.3 m) and -1.1 m/year (± 0.4 m). This phenomenon can be attributed to natural factors such as marine erosion, where the action of waves, currents and storms attacks the coastline, as well as subsidence, a sinking of the ground leading to progressive submersion. In addition, sea level rise, linked to climate change, accentuates erosion and submersion of low-lying areas, while a low sedimentary input, due to insufficient rivers and streams, limits the regeneration of the coastline.

Figure 23: Shoreline retrait in Pointe-Noire Region.

In parallel, anthropogenic factors such as the deforestation of mangroves, which plays a protective role against erosion, the extraction of sand which weakens the coastline, urbanization disrupting sedimentary dynamics, and port developments modifying coastal currents, also contribute to the acceleration of the erosive process and the regression of coasts in the region.

4.1.7. Ecological and Socio-Economic Implications of Coastal Dynamics

The coastal dynamics in Pointe-Noire, characterized by a contrast between erosion, accretion, and coastline retreat, generate significant ecological and socio-economic implications, considering the city's role as an economic capital and the presence of sensitive ecosystems.

- ✓ **Ecosystem Disruption and Biodiversity Loss**

Ecosystem disruption and biodiversity loss are major concerns. Coastal erosion and retreat directly threaten mangrove forests north of Pointe-Noire, which are crucial for coastal protection, soil stabilization, carbon sequestration, and habitat provision. Mangrove deforestation, whether caused by erosion or human activities, reduces the capacity to mitigate storms and floods, directly impacting biodiversity, especially fish, crustaceans, and birds. Seagrass beds and coral reefs are also affected by altered sedimentary dynamics, such as increased turbidity from erosion or burial from accretion. Beach erosion, notably at Côte Mateve, Matoumbi, Pointe-Indienne, and Djéno, destroys vital habitats for sea turtles, migratory birds, and invertebrates, reducing biodiversity and affecting ecological functions. Furthermore, Lakes Loubi, Loufouloukari, and Cayo, located south of Pointe-Noire, will be threatened by this erosion, with projections indicating a loss of over 200 meters of land to the ocean by 2100.

- ✓ **Social and Cultural Impacts**

Social and cultural impacts are particularly concerning for local communities, especially fishing villages. Land loss and housing destruction can lead to displacement, disintegration of traditional social structures, and loss of cultural identity. Erosion and marine ecosystem degradation affect food security and livelihoods, as communities depend on fishing. The decline in fish resources due to altered marine habitats deprives fishermen of income, increasing economic vulnerability, especially for those engaged in artisanal fishing. This situation exacerbates gender inequalities, as women play a key role in marine resource management and fish product trade. The city of Loango, rich in historical and cultural heritage, risks seeing its heritage sites and tourism potential compromised by coastal erosion, including the slave embarkation port (a UNESCO and national heritage site).

- ✓ **Economic Impacts**

Economic impacts are far-reaching, affecting key sectors such as fishing, tourism, commerce, and port activities. Fishing villages are vulnerable to coastal ecosystem degradation, leading to reduced fish catches and income. The tourism sector is threatened by beach loss and landscape degradation, negatively impacting hotels and restaurants near the sea. Small coastal businesses suffer losses due to infrastructure destruction, reducing economic activity and local jobs. Port activities are disrupted by accretion/siltation of channels (requiring costly dredging), and erosion threatens port infrastructure, complicating trade and increasing operating costs. These cumulative impacts necessitate urgent adaptation strategies to preserve vital sectors of the local economy.

- ✓ **Impact on Infrastructure**

Finally, the impact on infrastructure is significant. Coastline retreat leads to land loss, with important economic and social consequences for coastal populations. Coastal erosion damages coastal infrastructure, such as roads n°4, which connects Congo and Angola south of Pointe-Noire, and national road n°5, the main road connecting Pointe-Noire and Loango. The costs of repairing and reconstructing this damaged infrastructure can be substantial.

Part III: Scenarios, Projections, and Socio-Economic Impacts of Sea Level Rise

This section proposes to analyze sea level rise projections in Pointe-Noire according to different scenarios. First, a sea level rise scenario without the influence of climate change will be presented, modeling a rise in water levels at 0.5 m, 1 m, 2 m, and 3 m. Next, the effects of global warming on sea level evolution will be studied through a comparison of projections according to global warming. Finally, an analysis of tidal trends at horizons 2030, 2050, 2100, and 2152 will assess the evolution of coastal risks in the short, medium, and long term, and identify the resulting socio-economic issues.

4.1.8. Sea Level Rise Scenario without Climate Change

The results present simulations of sea level rise in Pointe-Noire, without considering the effects of climate change. This means that these scenarios do not take into account the accelerated melting of ice and thermal expansion of water due to global warming. Instead, they represent a sea level rise due to local or regional factors, such as tectonic movements, subsidence (sinking) of soils, or changes in ocean currents.

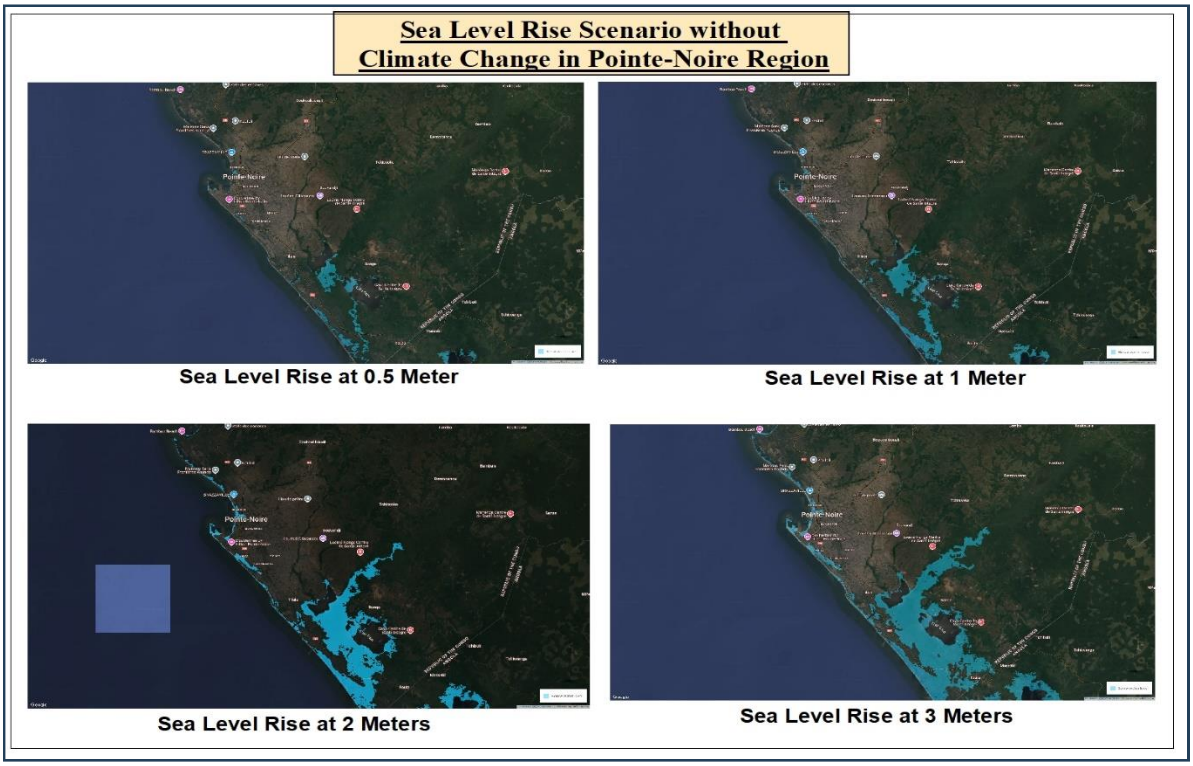

Figure 24: Sea level rise scenarios without climate change in Pointe-Noire region.

These results show the consequences of a sea level rise of 0.5 meters, 1 meter, 2 meters, and 3 meters. Regardless of the scenario (0.5m, 1m, 2m, 3m), marine submersion affects the Loufoulakari and Cayo lakes area south of Pointe-Noire. This vulnerability is due to the low topography of these sites, making them particularly sensitive to marine intrusion. In parallel, all scenarios show a more or less considerable impact on the port of Pointe-Noire. Even a modest sea level rise could disrupt port activities, damage infrastructure, and increase flood risks. On the other hand, sea level rise scenarios at 2 meters and 3 meters indicate a critical threshold beyond which the impact becomes widespread and potentially catastrophic for Pointe-Noire. The flooding of low-lying coastal areas becomes massive, threatening entire neighborhoods, vital infrastructure, and key ecosystems.

4.1.9. Sea Level Rise Scenario under the Effect of Climate Change

The results of mapping simulations illustrating the consequences of sea level rise (SLR) in Pointe-Noire for different global warming scenarios (1 to 1.5°C, 1.5 to 2°C, 2 to 2.5°C and 2.5 to 4°C) reveal a progressive increase in the extent of flooded areas depending on the level of warming. These simulations integrate the effects of thermal expansion of seawater and ice melt, based on climate models that project the evolution of temperatures and precipitation according to different greenhouse gas emission scenarios.

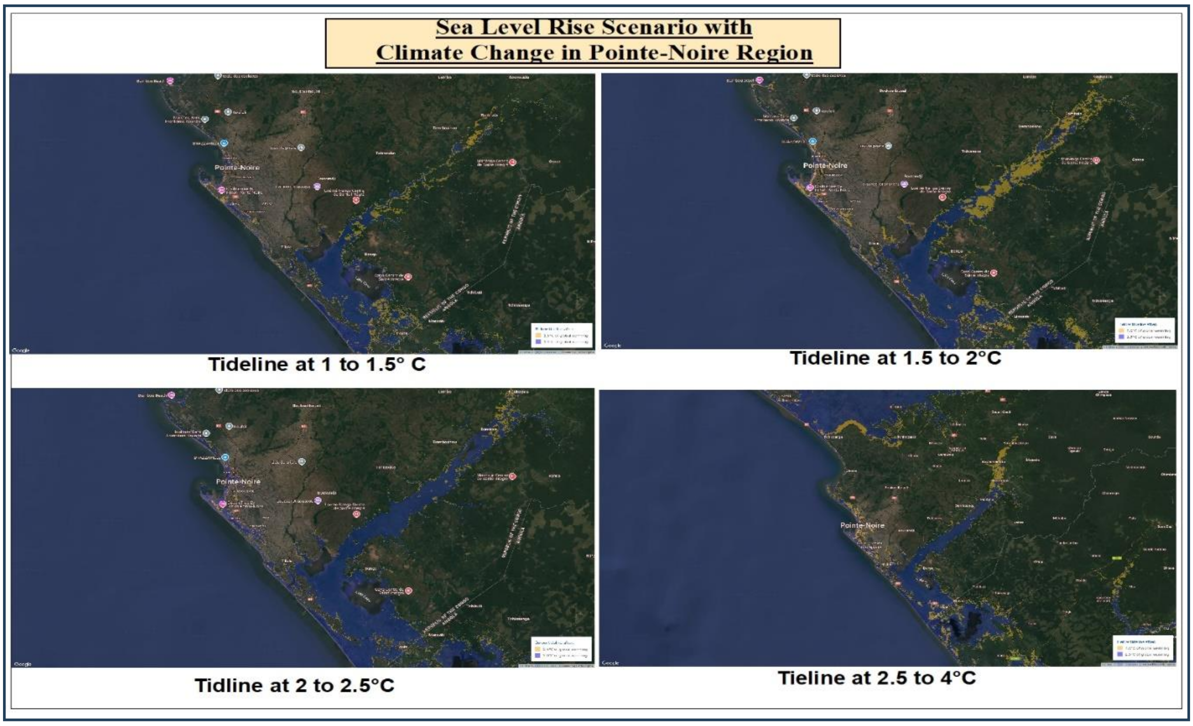

Figure 25: Sea level rise scenarios with climate change in Pointe-Noire region

The analysis of these simulations makes it possible to identify the area’s most vulnerable to flooding and to assess the potential impacts on the environment and infrastructure, highlighting the particular vulnerability of the Loufoulakari and Cayo lakes area, located south of Pointe-Noire, due to its low topography which makes it very sensitive to marine intrusion. In addition, the port of Pointe-Noire, a crucial economic infrastructure, is threatened by SLR, with an increase in the extent of flooded areas in the port area with the level of warming, which could lead to major disruptions in economic activities. The entire coastline of Pointe-Noire is also affected, with progressive flooding of low-lying coastal areas, degradation of marine ecosystems (mangroves), and loss of land. Finally, the simulations suggest that global warming exceeding 2°C could lead to potentially catastrophic consequences for Pointe-Noire, with widespread flooding of the coastline and major environmental impacts.

4.1.10. Projections of Sea Levels and Tides at Horizons 2030, 2050, 2100, and 2150

This section delves into the long-term outlook for Pointe-Noire, examining projections of sea levels and tidal patterns at specific future timeframes: 2030, 2050, 2100, and 2150. By analyzing these projections, we aim to understand the evolving coastal risks facing the region, assess the potential impacts of rising sea levels on key areas, and highlight the socio-economic challenges that may arise in the coming decades and centuries. This forward-looking analysis is crucial for informing adaptation strategies and ensuring the long-term sustainability of Pointe-Noire.

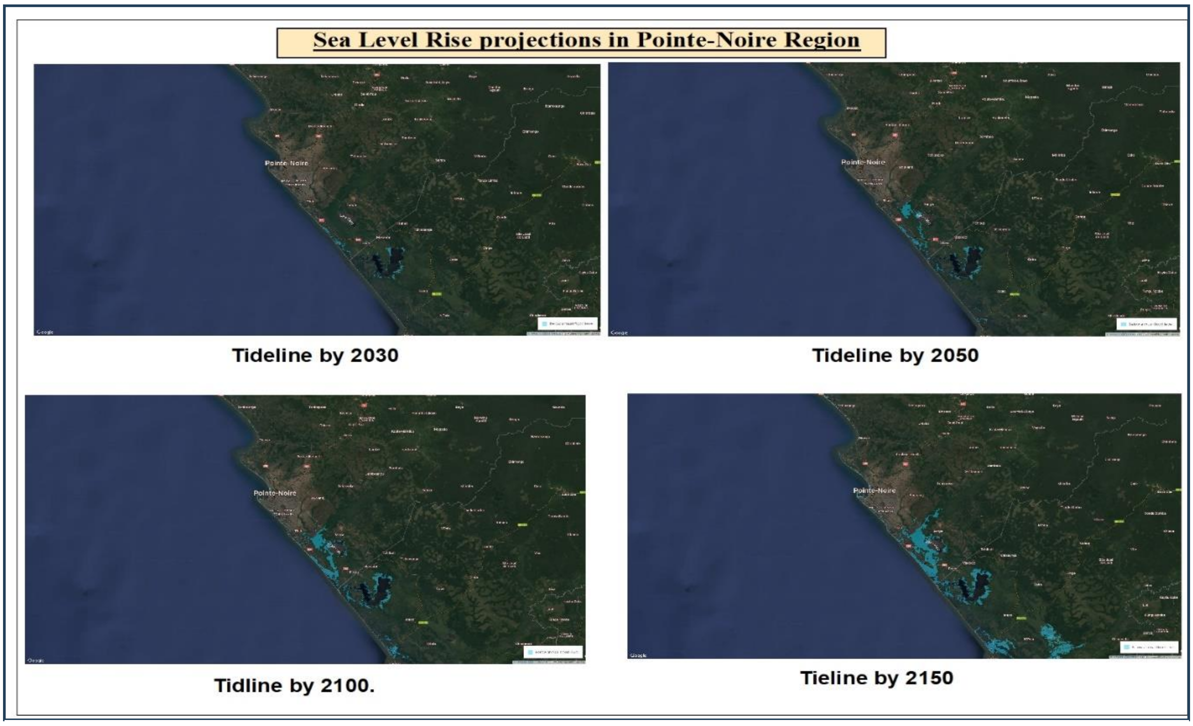

Figure 26: Projection of sea level rise in Pointe-Noire region.

Projections of sea level rise (SLR) in Pointe-Noire reveal a growing vulnerability of the region, with progressive flooding of coastal areas according to different time horizons and climate scenarios. The Loufoulakari and Cayo lakes area appears particularly exposed, experiencing notable flooding as early as 2030 and worsening in 2050, while the port of Pointe-Noire is also threatened, with increased risks to its infrastructure. The entire coastline is affected by coastal erosion and land loss, highlighting the need for adaptation measures. The projections for the years 2100 and 2150 respectively, present much more critical situations, with massive flooding of the Loufoulakari and Cayo lakes area, significant submersion of the port, and widespread coastal erosion. Compared to the projections for 2030 and 2050, these situations, which would occur in the more distant future, are less likely to occur in the short term, but remain possibilities to consider if greenhouse gas emissions are not reduced significantly.

4.1.11. Potential Impacts of Sea Level Rise on Pointe-Noire Bay

Sea Level Rise (SLR) in Pointe-Noire is emerging as a multi-dimensional challenge, with potential repercussions threatening to destabilize the socio-economic and environmental foundations of the region. This in-depth analysis explores the ramifications of SLR, highlighting the specific vulnerabilities of Pointe-Noire and building upon the previously conducted scenario analyses to better understand the extent of the risks involved.

4.1.11.1. Impacts on the Economic Sector:

- ✓ **Threat to port infrastructure**

The port of Pointe-Noire, the economic engine of the region, is directly threatened by SLR. Projections indicate increased risks to its infrastructure, which could lead to major disruptions in economic activities. Increased submersion of docks and storage areas could limit the port's capacity to accommodate large ships, thereby reducing the volume of trade. The costs of maintaining and repairing damaged infrastructure would increase, burdening public and private finances. As such, Hallegatte et al. (2013) emphasize that port cities are particularly vulnerable to the impacts of SLR, with potentially disastrous economic consequences.

- ✓ **Disruption of fishing activities**

Sea Level Rise could lead to the destruction of marine habitats essential for fish reproduction, thereby reducing fish stocks. Fishing communities, particularly the fishing village whose livelihoods depend directly on the availability of marine resources, would be particularly affected. A decrease in catches could lead to a rise in fish prices, affecting the diet of local populations.

- ✓ **Impact on tourism**

Sea level rise (SLR) could have significant consequences for the tourism sector in Pointe-Noire. The progressive submersion of beaches, hotel infrastructure located on the seafront, and coastal tourist sites could deter tourists from visiting the region. The loss of tourist appeal could lead to a drop in revenue for hotels, restaurants, travel agencies, and other businesses in the sector. In addition, the degradation of coastal landscapes and the loss of access to beaches could harm Pointe-Noire's image as an attractive tourist destination. Indeed, Nicholls et al. (2007) emphasize that coastal tourist areas are particularly vulnerable to the impacts of sea level rise. Hinkel et al. (2014) highlight the potential costs of adapting tourist infrastructure to SLR.

✓ **Impacts on coastal and petroleum companies**

SLR directly threatens the activities of companies located along the coast of Pointe-Noire, which are a pillar of the local economy. Among these companies, oil companies play a leading role. The submersion of facilities (refineries, oil terminals, logistics bases), erosion of land, and disruption of infrastructure (pipelines, access roads) could lead to production shutdowns, delays in exports, and considerable financial losses for oil companies. These disruptions could have significant repercussions on the tax revenues of the Congolese State, given the significant contribution of the oil sector to the national GDP. In addition, the costs of protecting and adapting oil infrastructure could be very high.

4.1.11.2. Social and Cultural Impacts:

✓ **Population displacement and health impacts**

The flooding of coastal areas could force populations to move to safer areas, leading to problems with housing, health, and access to basic services. Population displacements could also lead to social tensions, especially if the resources available in the host areas are limited. At the same time, Sea Level Rise could promote the spread of waterborne diseases, such as cholera and typhoid, due to the contamination of drinking water sources. The most vulnerable populations, such as children and the elderly, would be particularly exposed to these risks.

✓ **Job losses and increased precariousness**

The closure or relocation of coastal businesses, including oil companies, due to SLR, could lead to massive job losses, thus increasing the unemployment rate and the precariousness of local populations. The most vulnerable populations, such as young people, women, and low-skilled workers, would be particularly affected. The loss of jobs in the oil sector could have significant repercussions on household incomes and social stability. As the ILO (2018) points out, climate change can lead to job losses in some sectors, while creating new opportunities in others.

✓ **Loss of cultural heritage:**

Sea level rise (SLR) and coastal erosion could lead to the destruction of historical and cultural sites located on the seafront, depriving local communities of part of their identity and history. Indeed, Pointe-Noire and its surroundings possess a rich cultural heritage linked to the history of the region, including the old embarkation port located on the Loango site. This site, a witness to the history of the slave trade and past commercial exchanges, is particularly vulnerable to SLR and coastal erosion. The progressive submersion of this site, or its destruction by erosion, would lead to the loss of an important element of the cultural heritage of the region, depriving future generations of a tangible link with their past. The loss of cultural heritage could also have economic consequences, by reducing the tourist appeal of the region and limiting the possibilities for developing sustainable cultural tourism. It is also important to consider the potential loss of other cultural sites that are less well-known but just as important to local communities.

4.1.11.3. Environmental impacts

- ✓ **Degradation of coastal ecosystems**

Sea level rise (SLR) could lead to the destruction of mangroves, salt marshes, seagrass beds, and other coastal ecosystems that play an essential role in protecting the coastline against erosion and storms, as well as in maintaining biodiversity and providing essential ecosystem services. Mangroves, in particular, are valuable ecosystems that harbor a great diversity of animal and plant species, serve as nurseries for many species of fish and crustaceans, and contribute to carbon sequestration, thus mitigating climate change. The loss of these ecosystems, due to submersion, salinization, or erosion, could have disastrous consequences on local biodiversity, artisanal fishing, and the resilience of the coastline to extreme climatic events. The disappearance of mangroves could also lead to an increase in coastal erosion, making coastal communities even more vulnerable to the impacts of SLR.

- ✓ **Salinization of fresh water**

The intrusion of salt water, exacerbated by SLR, threatens the quality of fresh water essential to Pointe-Noire and its surroundings. Lakes Cayo and Loufoulakari, as well as the Songolo and Loango rivers, are particularly vulnerable to salinization. The salinization of these sources of fresh water could compromise the supply of drinking water to local populations, affect agriculture (especially market gardening and fruit crops that depend on irrigation), and disrupt aquatic ecosystems by altering the composition of species and promoting the proliferation of halophilic (salt-tolerant) species. The salinization of soils could also reduce the fertility of agricultural land and affect local food production. The loss of fresh water could also lead to conflicts related to access to water between different users (populations, farmers, industries). As White et al. (2007) highlight the risks of salinization of fresh water due to SLR. Herbert et al. (2015) analyze the impacts of salinization on coastal ecosystems.

- ✓ **Exacerbation of coastal erosion**

SLR intensifies coastal erosion, leading to increased land loss and threatening infrastructure located on the seafront, as well as natural habitats such as beaches and dunes. Coastal erosion can be exacerbated by natural factors (waves, marine currents, storms) and anthropogenic factors (deforestation of mangroves, sand extraction, construction of coastal infrastructure). SLR amplifies these processes by increasing the frequency and intensity of coastal floods and by weakening coastal ecosystems that protect the coastline. The loss of land due to coastal erosion can lead to the displacement of populations, the destruction of infrastructure (roads, buildings, sanitation networks), and the loss of natural habitats, thus reducing biodiversity and ecosystem services (protection against storms, soil stabilization, etc.). The disappearance of beaches and dunes can also have negative consequences on tourism and recreational activities.

4.2. DISCUSSION

Part I: Discussion on climate change and its consequences in the Pointe Noire region.

4.2.1. Discussion of rainfall variability

The analysis of rainfall patterns in Pointe-Noire reveals a tropical climate with a distinct wet and dry season, potentially bimodal, aligning with climate classification methods (DAGBA, 1989). Peak rainfall in February, March, and November suggests a prominent rainy season, while a decline from April to August, with a minimum in July-August, hints at a bimodal pattern. This seasonal variation impacts water resources, urban activities, and soil erosion, requiring careful water management during dry periods and mitigation strategies for flood and erosion risks during heavy rainfall. To further understand precipitation trends, especially extreme events, we can draw insights from (MASSOUANGUI-KIFOUALA et al. 2020), which provide rigorous methodologies and specific data on Pointe-Noire's rainfall evolution. MASSOUANGUI-KIFOUALA's (2022) study indicates increasing trends in annual rainfall totals and precipitation intensity, yet decreasing trends in very and extremely wet days, highlighting the complex evolution of Pointe-Noire's rainfall regime (MASSOUANGUI-KIFOUALA et al. 2020). Coupled with interannual variability assessable via the SPI index, these trends suggest potential future exacerbation of environmental issues like flooding and erosion, as projections to 2070 indicate a generalized increase in rainfall (MASSOUANGUI-KIFOUALA et al. 2020). Furthermore, the vulnerability of the Republic of the Congo's coastline to erosion, exacerbated by climate change and rainfall variability, as discussed by SITOU and NGOMA MBOUMBOU (2023), underscores the need for comprehensive strategies that consider both rainfall patterns and coastal resilience.

4.2.2. Discussion of temperature trends

The analysis of temperature trends in Pointe-Noire from 1981 to 2023 reveals a gradual warming trend, consistent with previous studies in the region (MASSOUANGUI-KIFOUALA et al. 2020). The observed average temperature increase of +0.023°C per year aligns with the broader context of progressive climate warming detected over a longer period (1950-2010) (MASSOUANGUI-KIFOUALA et al. 2020). Furthermore, our description of seasonal temperature variations corresponds with available climatological data, highlighting established characteristics of Pointe-Noire's climate, such as the warm, humid season from January to May and the cooler, drier season from June to September (DAGBA, 1989).

MASSOUANGUI-KIFOUALA et al. (2020) provide additional insights by analyzing not only average temperatures but also temperature extremes, revealing increasing trends in both minimum and maximum temperatures (MASSOUANGUI-KIFOUALA et al. 2020). This increase in extremes, combined with the observed increase in average temperature, underscores the extent of climate warming in the region. The study also highlights an increase in hot days and nights, as well as a decrease in relatively cool nights and days (MASSOUANGUI-KIFOUALA et al. 2020). These trends in extreme temperature events corroborate our detected general warming trend and emphasize the significant changes occurring in the city's thermal regime, underscoring the need for continued climate monitoring and the development of adaptation strategies (MASSOUANGUI-KIFOUALA et al. 2020).

4.2.3. Discussion of temperature trends

Our analysis of the impact of climate change on erosion in Pointe-Noire highlights the increasing climatic aggressiveness in the region, encompassing the intensification of extreme weather events, a major concern for coastal areas (SITOU and NGOMA MBOUMBOU, 2023). The identified irregularity of precipitation in Pointe-Noire and Loango, with alternating heavy rains and seasonal droughts, is a key factor contributing to erosion, accentuating soil erosion and ecosystem degradation. MASSOUANGUI-KIFOUALA's (2022) study reveals increasing annual rainfall totals combined with decreasing very and extremely wet days, suggesting more intense rainfall episodes over shorter periods, likely increasing runoff and water erosion.

We rightly emphasize sea-level rise as a major threat to Pointe-Noire and Loango's coastal areas, increasing coastal erosion. This is central to SITOU and NGOMA MBOUMBOU's (2023) assessment of the Congolese coastline's vulnerability, projecting significant coastline retreat in the bays of Pointe-Noire and Loango. Enhanced storms and ocean swells are also important drivers of coastal erosion, promoting coastline retreat and land salinization. Our analysis of evolving erosive capacity highlights the role of heavy rainfall leading to significant runoff and increased water erosion, with a high climatic aggressiveness index contributing to ravine formation and removal of fertile layers, consistent with the fragility of Pointe-Noire's soils (SITOU and NGOMA MBOUMBOU, 2023). Furthermore, MOUNGANGA (2023) compares coastal erosion vulnerability in Libreville and Pointe-Noire, highlighting that uncontrolled coastal exploitation and coastal development also significantly contribute to erosion aggravation, in addition to climatic aggressiveness.

Part II: Discussion on Dynamics and Impacts of Coastal Erosion in Pointe-Noire.

4.2.4. Discussion on Coastal Accretion

The diachronic analysis of the Pointe-Noire coastline (2000-2023) reveals contrasting erosion dynamics, corroborated by the work of Mounganga (2023) and Sitou (2013), which highlight the complex interaction of natural and anthropogenic factors. Pronounced erosion in the downtown and port area is strongly influenced by port and industrial infrastructure, interrupting natural sedimentary transit and artificializing the coastline, thereby reducing its adaptive capacity (Mounganga, 2023; Sitou, 2013). To the north, older erosion, exacerbated by the presence of marshes and the intensification of storms linked to climate change, demonstrates the hydromorphological vulnerability of the area (Mounganga, 2023), combined with low sedimentary replenishment (Sitou, 2013). Finally, in the south, increasing urbanization destabilizes the dune cordon and modifies coastal currents, inducing a progressive intensification of erosion (Mounganga, 2023; Sitou, 2013).

4.2.5. Discussion on Coastal Retreat

The analysis of coastal accretion zones in Pointe-Noire opens an interesting perspective to complement existing studies, which focus mainly on erosion phenomena (Sitou and Ngoma, Mboumbou). While these studies highlight the negative impact of port developments on coastal stability, our results highlight significant accretion zones north of the port, suggesting a redistribution of sediments induced by these same activities. As Vennetier pointed out, port development has profoundly modified the sedimentary dynamics of Pointe-Noire. Our observations confirm this transformation, showing that dredging operations and modifications of coastal currents (Kitsoukou) associated with port infrastructure create sand deposition zones. The question that then arises is how to optimize the management of these sediments, in order to minimize erosion in other sectors of the coastline and transform this constraint into an opportunity, by using the dredged sediments to strengthen vulnerable areas. This approach, which consists of considering the coastline as a complex dynamic system where erosion and accretion are intimately linked, seems essential for sustainable coastal management of Pointe-Noire.

4.2.6. Discussion of historical evolution of the coastline

The identification of zones of coastline retreat north and south of Pointe-Noire reveals a coastal dynamic marked by significant erosion. The observed retreat rates, reaching -2.5 m/year (± 0.4 m) in the north and -1.5 m/year (± 0.3 m) in the south, confirm a general trend of intense marine erosion affecting the Congolese coastline, as highlighted by Sitou and Ngoma Mboumbou. Although the sources do not always detail these specific speeds for these precise areas, they clearly establish a general trend of coastline retreat.

The interpretation of these retreat zones through the prism of natural factors finds substantial echo in the existing literature. Marine erosion, orchestrated by the action of waves, currents and storms, is recognized as a primary driver of coastal dynamics (Paskoff and Chaibi). Similarly, sea-level rise, a direct consequence of climate change, exacerbates this vulnerability by accentuating erosion and submersion of low-lying areas (Ozer, Hountondji and De Logueville). The hypothesis of low sedimentary input, limiting the regeneration capacity of the coastline, is also relevant in the context of the activity of coastal rivers, whose economic importance and hydrological study have been relatively neglected according to some sources.

In parallel, the analysis of anthropogenic factors as contributors to the acceleration of this coastal retreat is amply supported. Deforestation of mangroves, whose protective role against erosion is crucial, is a well-established aggravating factor. Sand extraction, weakening the coastline by reducing the sedimentary stock, is also pointed to (Mounganga). Urbanization, by disrupting natural sedimentary balances, and port developments, whose modifications of coastal currents can have erosive consequences downstream, are all human interventions that amplify the natural dynamics of erosion. Sitou and Ngoma Mboumbou highlight the impact of the extension of the port of Pointe-Noire on the sedimentary balance, a disturbance that could explain the retreat zones observed north and south of the port area.

Part III: Discussion on Scenarios, Projections, and Socio-Economic Impacts of Sea Level Rise

4.2.7. Discussion of historical evolution of the coastline

The findings regarding the marine submersion of Lakes Loufoulakari and Cayo, as well as the impact on the port of Pointe-Noire, require a thorough analysis in light of available data and previous discussions. It appears that low-lying areas, such as Lakes Loufoulakari and Cayo south of Pointe-Noire, exhibit a particular sensitivity to marine intrusion, regardless of sea-level rise related to global climate change. This vulnerability of low coasts is a major concern, especially since Lake Cayo, described by Vennetier (1968) as a marshy area, is inherently susceptible to submersion. Similarly, the impact on the port of Pointe-Noire manifests regardless of the sea-level rise scenario, which is consistent with its coastal location and its crucial role for the regional economy (Vennetier, 1968; Sitou and Ngoma Mboumbou, 2023; Ngueuko and Adewumi, 2020; WACA, 2013). Thus, even a modest increase in sea level could disrupt port activities, damage infrastructure, and increase the risk of flooding, as suggested by studies on the vulnerability of coastal infrastructure (Sitou and Ngoma Mboumbou, 2023; Ngueuko and Adewumi, 2020; Brown et al., 2010; IRSEN, 2019).

Furthermore, the critical threshold identified between 2 and 3 meters of sea-level rise indicates a point beyond which the impact becomes widespread and potentially catastrophic for Pointe-Noire. Indeed, the massive flooding of low-lying coastal areas, threatening entire neighborhoods, vital infrastructure, and key ecosystems, is consistent with projections of increased coastal flooding in the event of sea-level rise (Sitou and Ngoma Mboumbou, 2023; Ngueuko and Adewumi, 2020; Brown et al., 2010; IRSEN, 2019). In addition, the bay of Pointe-Noire, already subject to erosion (Sitou and Ngoma Mboumbou, 2023; Ngoma Mboumbou, 2019), could see this phenomenon worsen with sea-level rise, even of local origin. The vulnerability of the Congolese coastline is also attributed to the presence of highly erodible sandy rocks and the low resilience of the population (Sitou and Ngoma Mboumbou, 2023; Ngueuko and Adewumi, 2020). Finally, the limited existence of effective protection measures along the coast, outside of the port itself, makes the region particularly sensitive to the effects of rising waters.

4.2.8. Discussion on Sea Level Rise under Climate Change

Sea-level rise (SLR) simulations for Pointe-Noire under global climate change, complementing analyses focused on local and regional factors, reveal a progressive increase in flooded areas depending on the intensity of warming (1 to 1.5°C, 1.5 to 2°C, 2 to 2.5°C, and 2.5 to 4°C), corroborating the general trends observed by the IPCC (2013). These simulations highlight the particular vulnerability of the Lakes Loufoulakari and Cayo area, already identified by Vennetier (1968) as a low-lying and marshy zone, as well as the growing threat to the port of Pointe-Noire, a crucial economic infrastructure (Vennetier, 1968; L. SITOU, D.A. NGOMA MBOUMBOU, 2023; J. Ngueuko and I. Adewumi, 2020; Ngoma Mboumbou et al., 2019). The entire coastline of Pointe-Noire is affected by these projections, with progressive flooding of low-lying coastal areas, potential degradation of marine ecosystems (J. Ngueuko and I. Adewumi, 2020; IRSEN, 2019), and land loss, a coastal erosion phenomenon already observed (Sitou and Ngoma Mboumbou, 2023; Ngoma Mboumbou et al., 2019).

Alarmingly, the simulations suggest that global warming exceeding 2°C could lead to potentially catastrophic consequences for Pointe-Noire, with widespread coastal flooding and major environmental impacts. This 2°C threshold is often considered a critical point beyond which risks increase exponentially (UNECA, 2014; Sally Brown et al., 2010, 2022). The low resilience of the population and the presence of highly erodible sandy rocks on the Congolese coastline (Sitou and Ngoma Mboumbou, 2023) could amplify these disastrous consequences in the absence of adequate protection measures and integrated planning that takes these future scenarios into account. Concurrently, the entire coastline of Pointe-Noire is affected by these projections, with progressive flooding of low-lying coastal areas, potential degradation of marine ecosystems such as mangroves, whose protective role against erosion has been mentioned (J. Ngueuko and I. Adewumi, 2020; Sally Brown et al., 2010; IRSEN, 2019), and land loss, a coastal erosion phenomenon already observed by Sitou and Ngoma Mboumbou (2023) and NGOMA MBOUMBOU Denis Aurélien et al. (2019).

4.2.9. Discussion on sea level rise projections

The trajectory of Pointe-Noire, scrutinized through the lens of sea-level rise (SLR) projections, reveals a growing vulnerability that unfolds like a dystopian narrative. As early as 2030, the notable flooding of Lakes Loufoulakari and Cayo, those coastal sentinels, heralds the beginning of an era of instability, echoing the concerns expressed by Nicholls and Cazenave (2010) regarding the imminent impact of SLR on low-lying areas. The port of Pointe-Noire, a vital artery of the regional economy, sees its foundations threatened, a foreshadowing of the infrastructural challenges highlighted by Hallegatte et al. (2013) in their analysis of the vulnerability of coastal cities to climate change. Coastal erosion, meanwhile, manifests as an inexorable process, reshaping the coastline and threatening riverside communities, a phenomenon documented by Luijendijk et al. (2018) in their global mapping of the evolution of sandy coasts.

Moving towards the horizon of 2050, the narrative darkens. The intensification of the flooding of Lakes Loufoulakari and Cayo, transforming precious ecosystems into submerged areas, illustrates the loss of biodiversity and population displacements anticipated by the IPCC (2014) in its report on impacts, adaptation, and vulnerability. The port, facing increasing operational challenges, embodies the need for massive investments in adaptation, a central theme in the work of Hinkel et al. (2014) on the costs of coastal adaptation. The projections for 2100 and 2150, although situated in a more distant future, present an alarming climax. The massive flooding of Lakes Loufoulakari and Cayo, the significant submersion of the port, and generalized coastal erosion outline a potentially catastrophic scenario, in line with the warnings of Rahmstorf (2007) on the consequences of sea-level rise beyond critical thresholds.

CONCLUSION ET RECOMMANDATIONS

CONCLUSION

This study has provided a comprehensive assessment of the multifaceted challenges posed by climate change, coastal erosion, and sea-level rise to the Pointe-Noire region of the Republic of Congo. Through a combination of historical data analysis, future climate projections, and vulnerability assessments, this research has illuminated the complex interplay between climatic factors, human activities, and coastal dynamics that are shaping the region's present and future.

Key findings demonstrate a clear trend of increasing climatic aggressiveness, characterized by rising temperatures, altered rainfall patterns, and heightened risks of extreme weather events. These changes are exacerbating coastal erosion, leading to significant land loss, infrastructure damage, and disruption of vital economic sectors, including maritime trade, fishing, and tourism. The diachronic analysis of the coastline revealed spatially variable erosion patterns, with the downtown and port area being particularly vulnerable due to the combined effects of port development and natural processes. While localized areas of accretion were identified, the overall trend indicates a net loss of coastal land, threatening ecosystems, communities, and cultural heritage sites.

Sea-level rise projections, both with and without the influence of climate change, paint a concerning picture for the future of Pointe-Noire. Even under moderate warming scenarios, significant portions of the coastline, including the ecologically sensitive Loufoulakari and Cayo lakes area and the economically critical port infrastructure, are at risk of inundation. The potential socio-economic consequences are far-reaching, encompassing population displacement, job losses, health impacts, and the degradation of essential ecosystem services.

In conclusion, this research underscores the urgent need for proactive and integrated strategies to mitigate the impacts of climate change and enhance the resilience of the Pointe-Noire region. The findings provide a robust scientific basis for informed decision-making and the development of effective adaptation measures to protect coastal communities, infrastructure, and ecosystems from the growing threats of a changing climate. The dedication expressed in the memory of your mother and the acknowledgement of all those who suffer from the environmental crisis should serve as a constant reminder of the human dimension of this challenge and the importance of pursuing a just and sustainable future.

RECOMMENDATIONS

Based on the findings of this study, the following recommendations are proposed to address the challenges of climate change, coastal erosion, and sea-level rise in the Pointe-Noire region:

- ☑ **Strengthen Climate Monitoring and Research:**
  - ✓ Enhance the network of meteorological stations and monitoring systems to improve the accuracy and resolution of climate data.
  - ✓ Invest in advanced climate modeling and downscaling techniques to generate more localized and reliable future climate projections.
  - ✓ Promote interdisciplinary research to better understand the complex interactions between climate change, coastal processes, and socio-economic systems.
- ☑ **Develop Integrated Coastal Zone Management Plans:**
  - ✓ Implement comprehensive coastal zone management plans that integrate climate change considerations into land-use planning, infrastructure development, and resource management.
  - ✓ Prioritize the protection and restoration of natural coastal habitats, such as mangroves, which provide valuable ecosystem services, including coastal protection and carbon sequestration.
  - ✓ Establish setback zones and building codes that account for future sea-level rise and erosion risks.
- ☑ **Invest in Adaptation Measures:**
  - ✓ Construction of coastal defenses, such as seawalls and breakwaters, in strategic locations.
  - ✓ Beach nourishment and dune stabilization projects to enhance natural coastal protection.
  - ✓ Elevating or relocating vulnerable infrastructure and housing.
  - ✓ Developing early warning systems for coastal flooding and erosion events.
  - ✓ Ensure that adaptation measures are implemented equitably and do not disproportionately burden vulnerable population

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